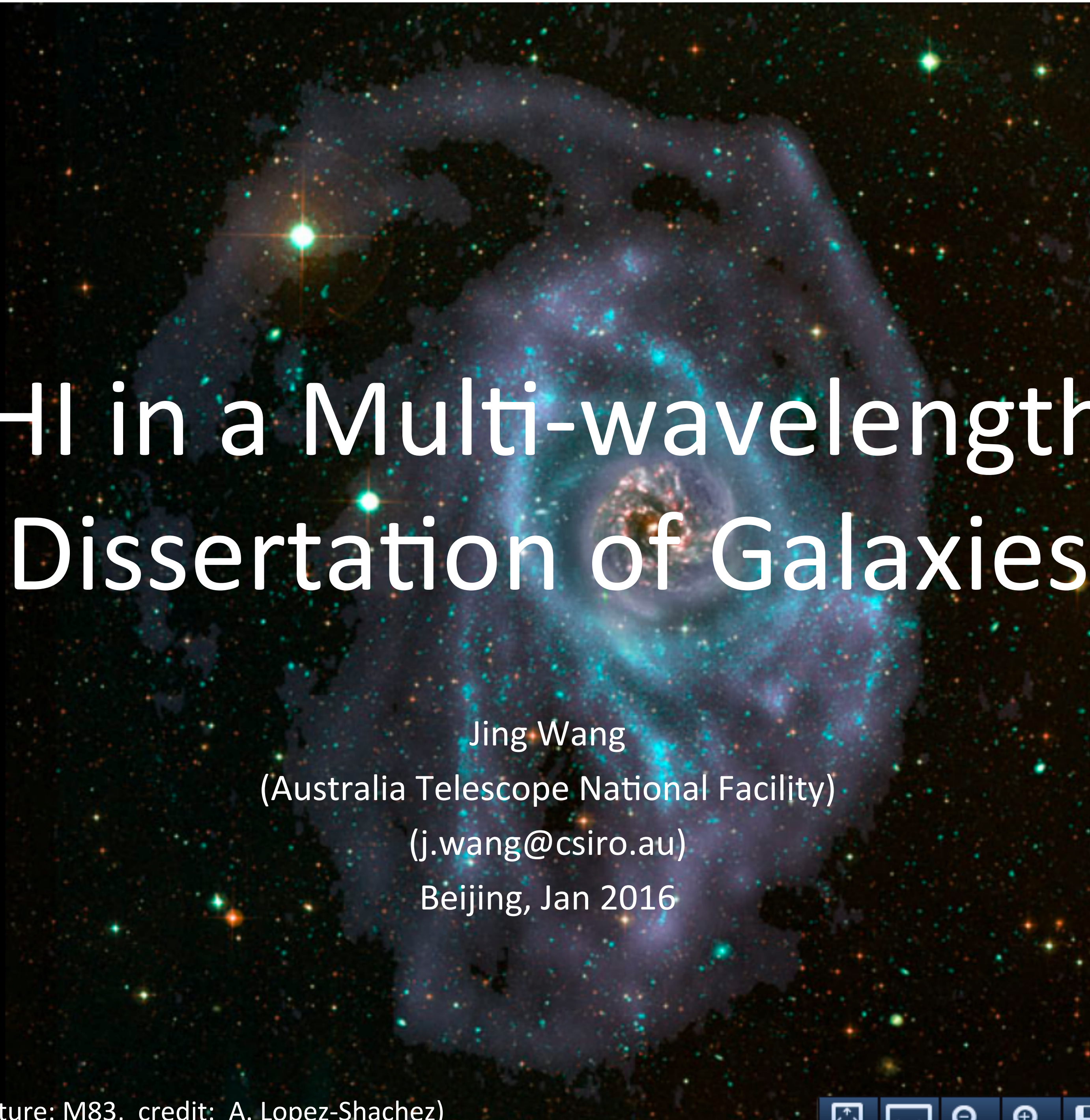


HI in a Multi-wavelength Dissertation of Galaxies

Jing Wang

(Australia Telescope National Facility)

(j.wang@csiro.au)

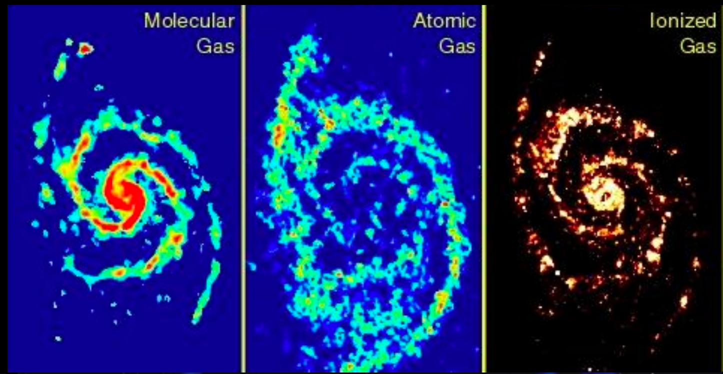
Beijing, Jan 2016

(Background picture: M83, credit: A. Lopez-Shachez)

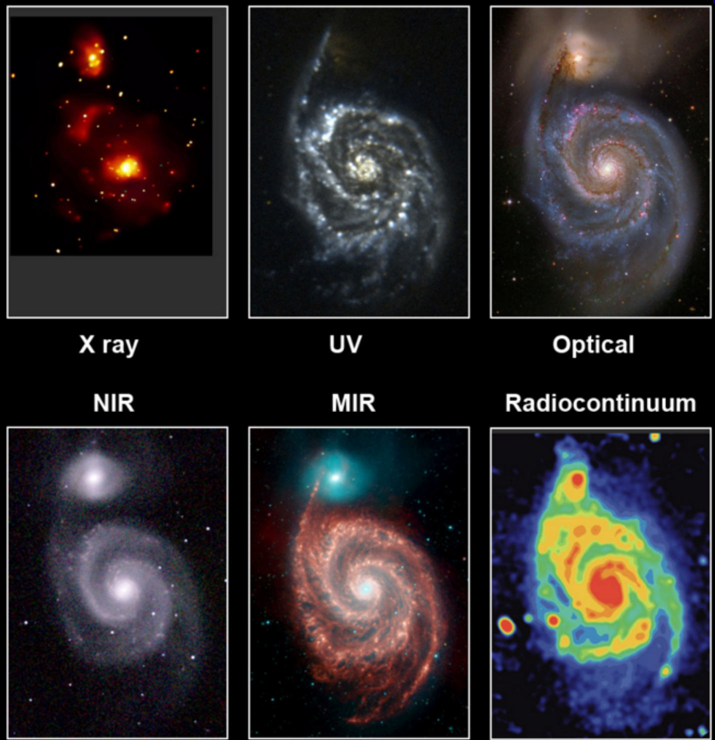
The introduction

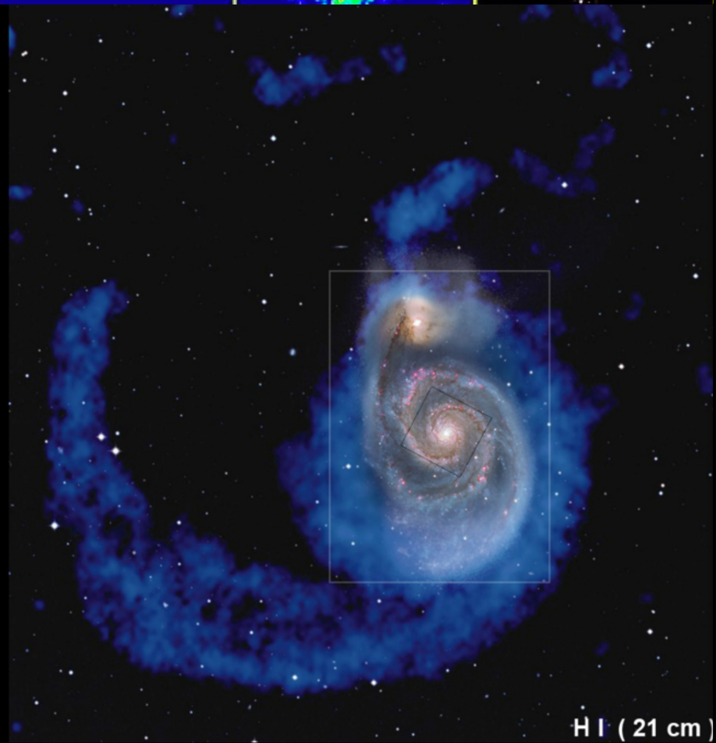
AN HI AND MULTI-WAVELENGTH VIEW OF GALAXIES

The many faces of Whirlpool galaxy (M51)

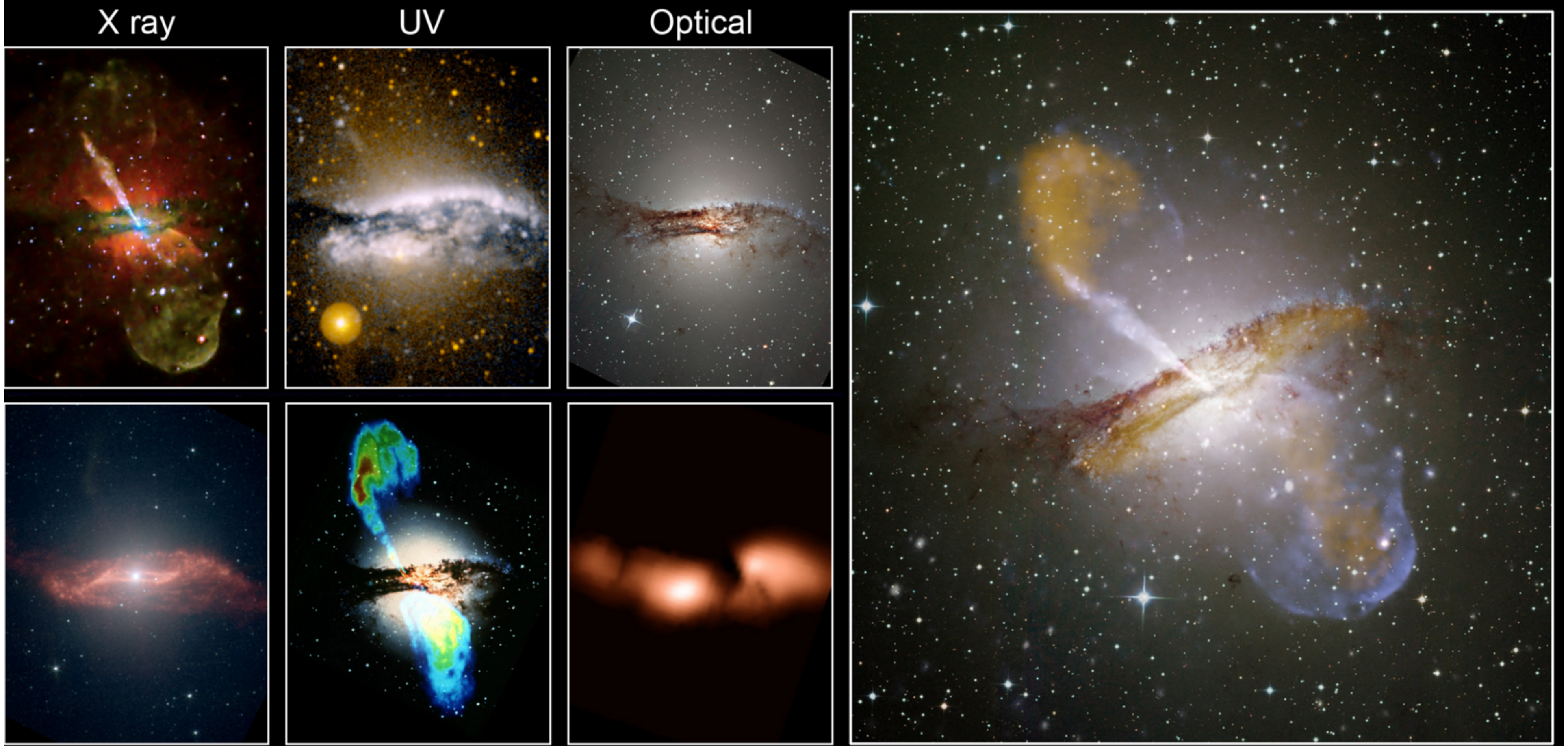


(Credit: A. Lopez-Shachez, S. Vogel)



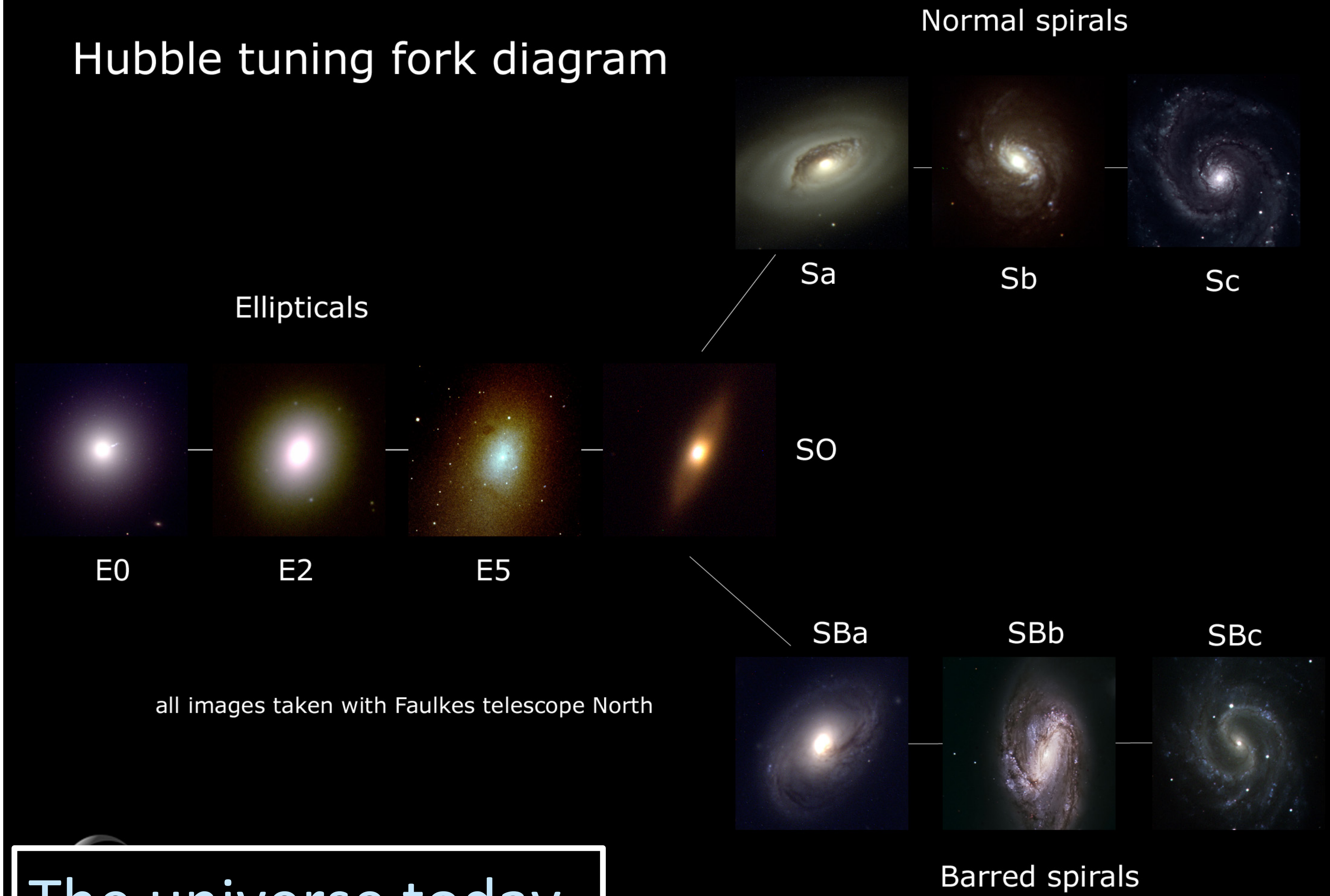


The many faces of Centurus A (NGC5128)



(Credit: A. Lopez-Shachez)

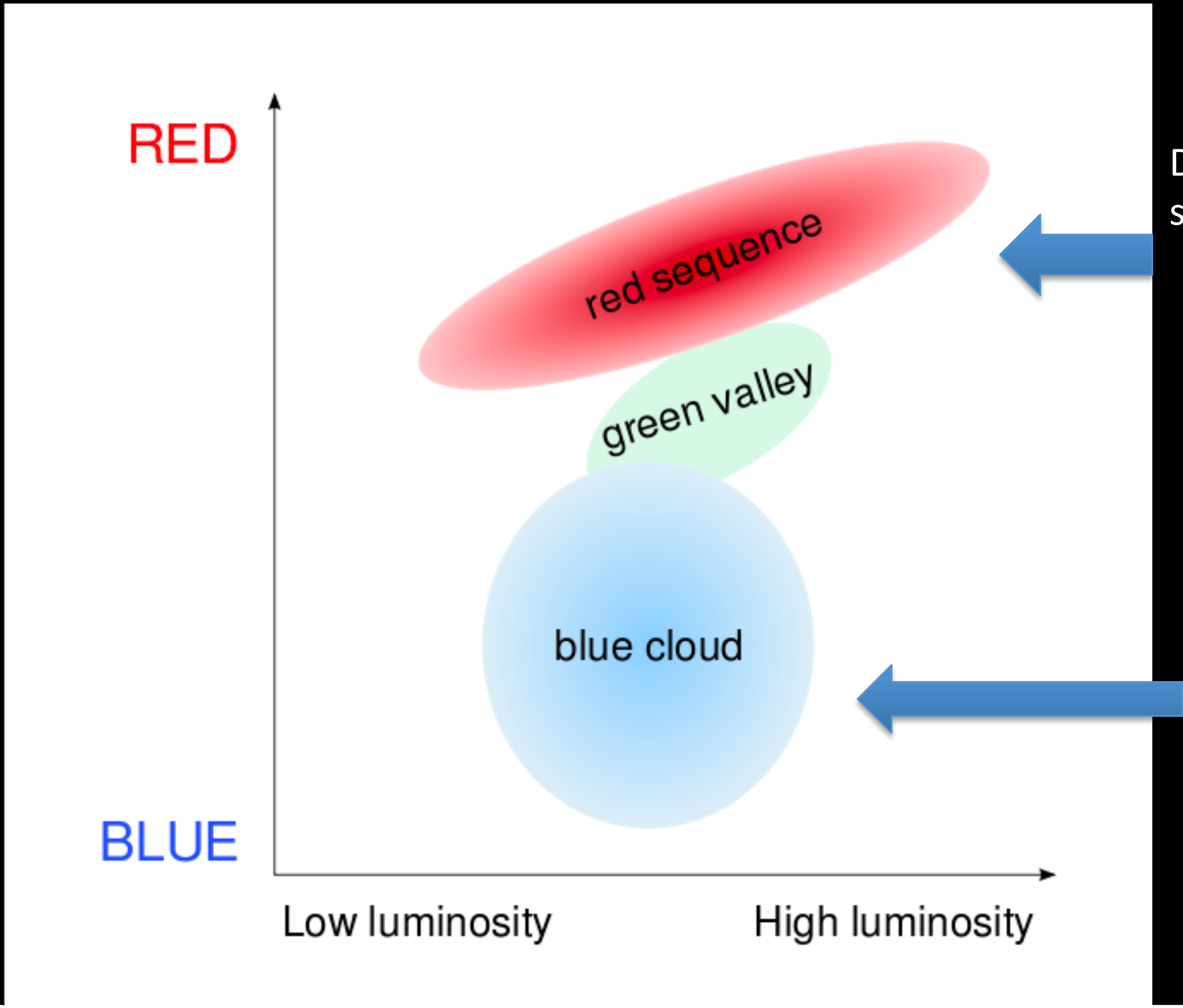
Hubble tuning fork diagram



all images taken with Faulkes telescope North

The universe today

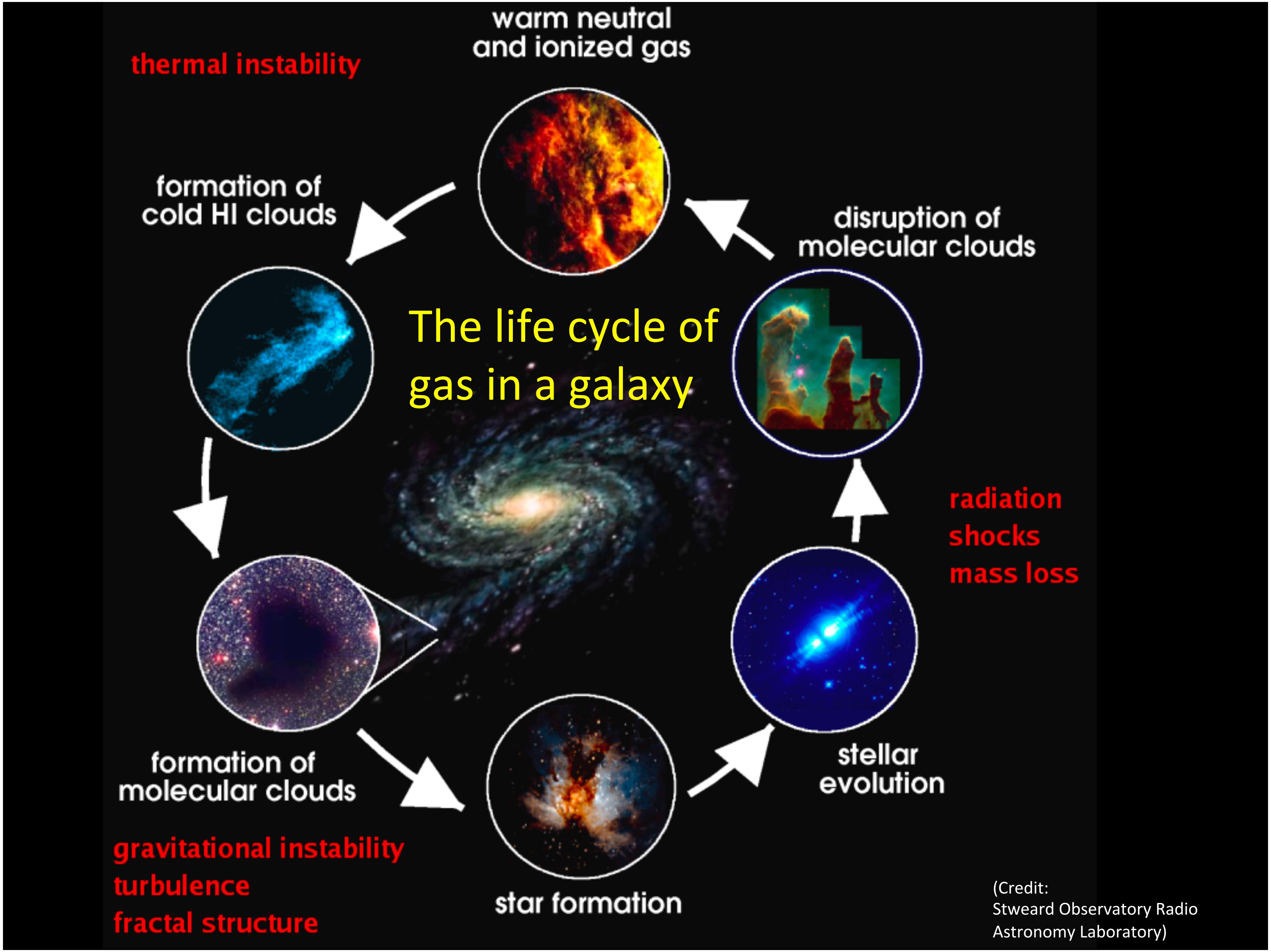
The colour-magnitude diagram



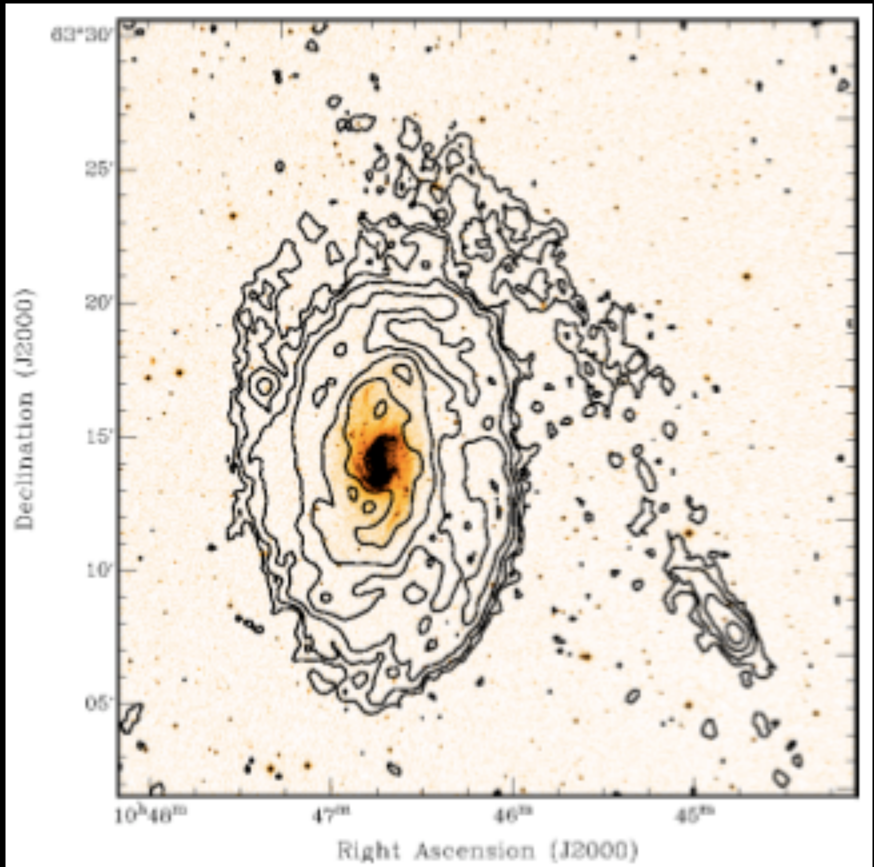
Dominated by old stars

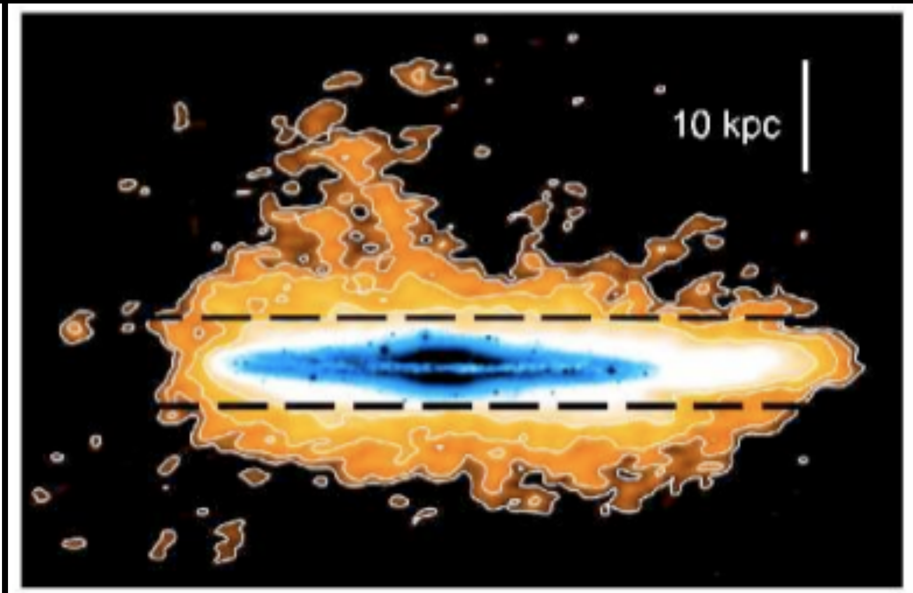
Dominated by young stars

Credit: wiki


The life cycle of gas in a galaxy
warm neutral and ionized gas
thermal instability
formation of cold HI clouds
formation of molecular clouds
gravitational instability
turbulence
fractal structure
star formation
stellar evolution
radiation
shocks
mass loss
disruption of molecular clouds
(Credit:
Stweard Observatory Radio
Astronomy Laboratory)

Source of cold gas



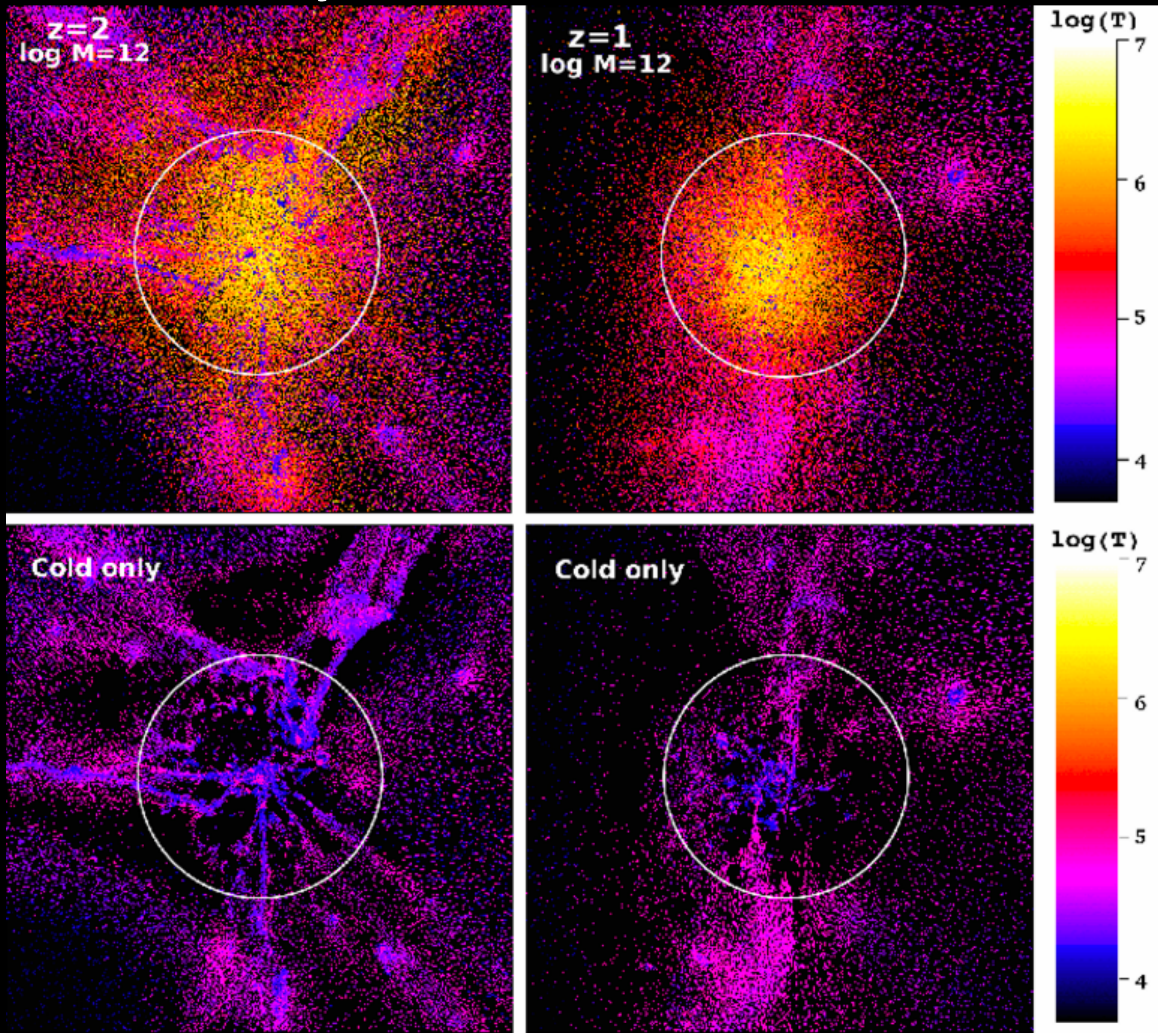


Source of gas：
- The IGM ("cold" and hot mode)
- Gas rich satellite galaxies

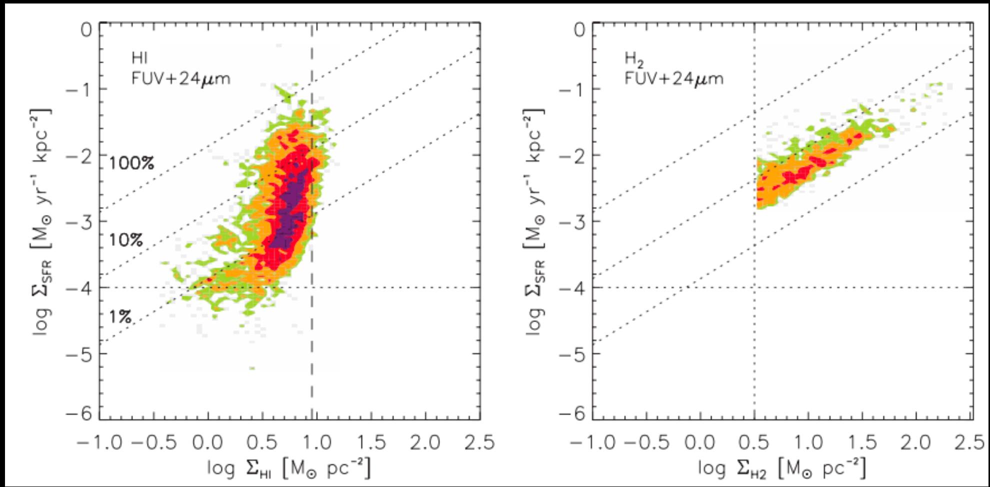
More than half of the mass of baryons are not in stars
If no feedbacks, these baryons would cool and be accreted

(Picture credit: T. Oosterloo)

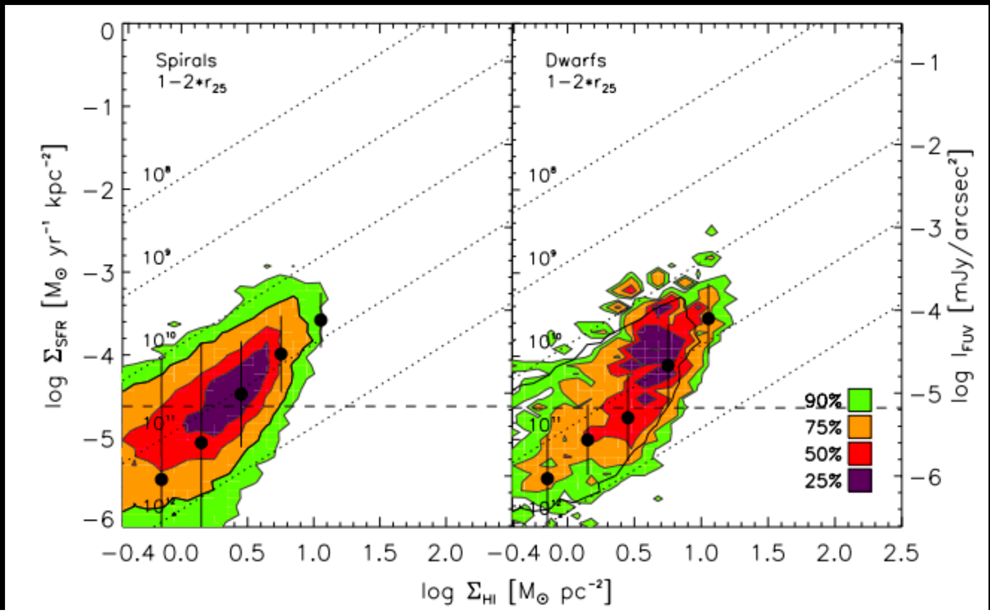
The cold and hot mode accretion predicted by theoretical simulations



Star formation traced by HI



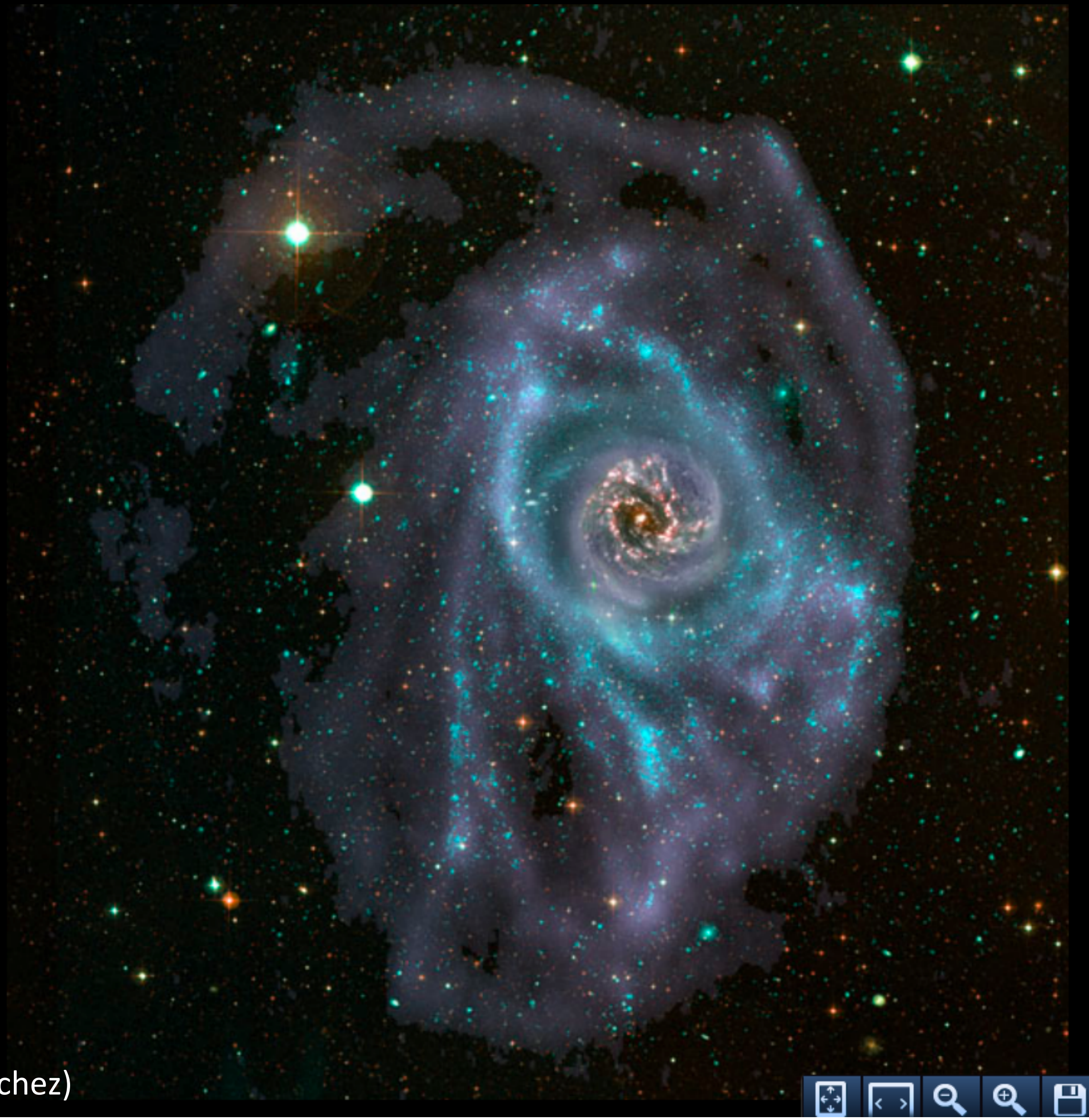
H2 dominated regions: the relation between HI and SFR is disrupted



HI dominated regions: HI seems to be a key parameter in setting the SFR

(credit: Bigiel+08, 10)

The XUV disk in M83 traced by HI



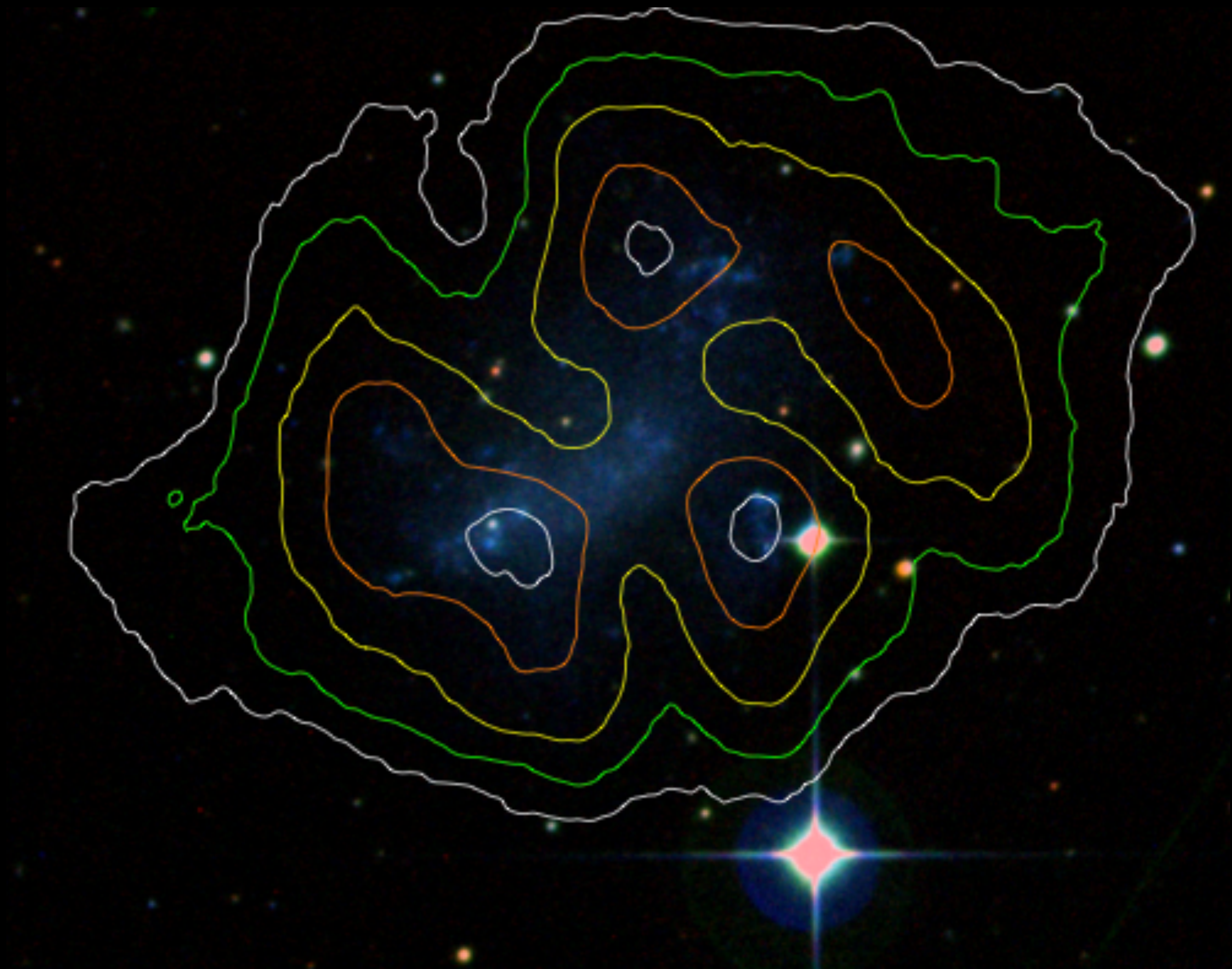
Red: optical

Blue: Far-ultraviolet

Grey: HI

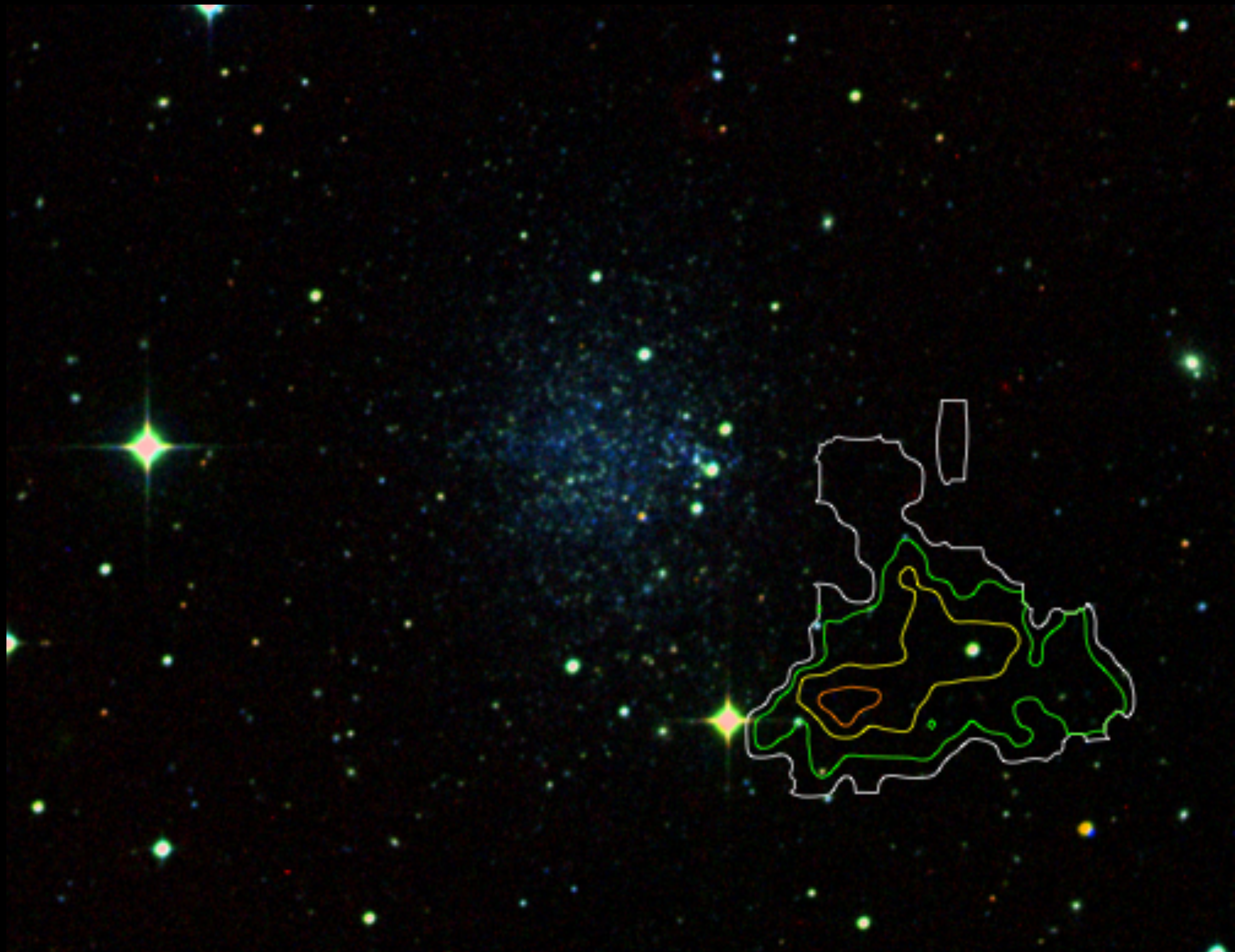
(credit: A. Lopez-Shachez)

Star forming regions traced by HI in a dwarf galaxy (ESO245-G005)



(Credit: LVHIS)

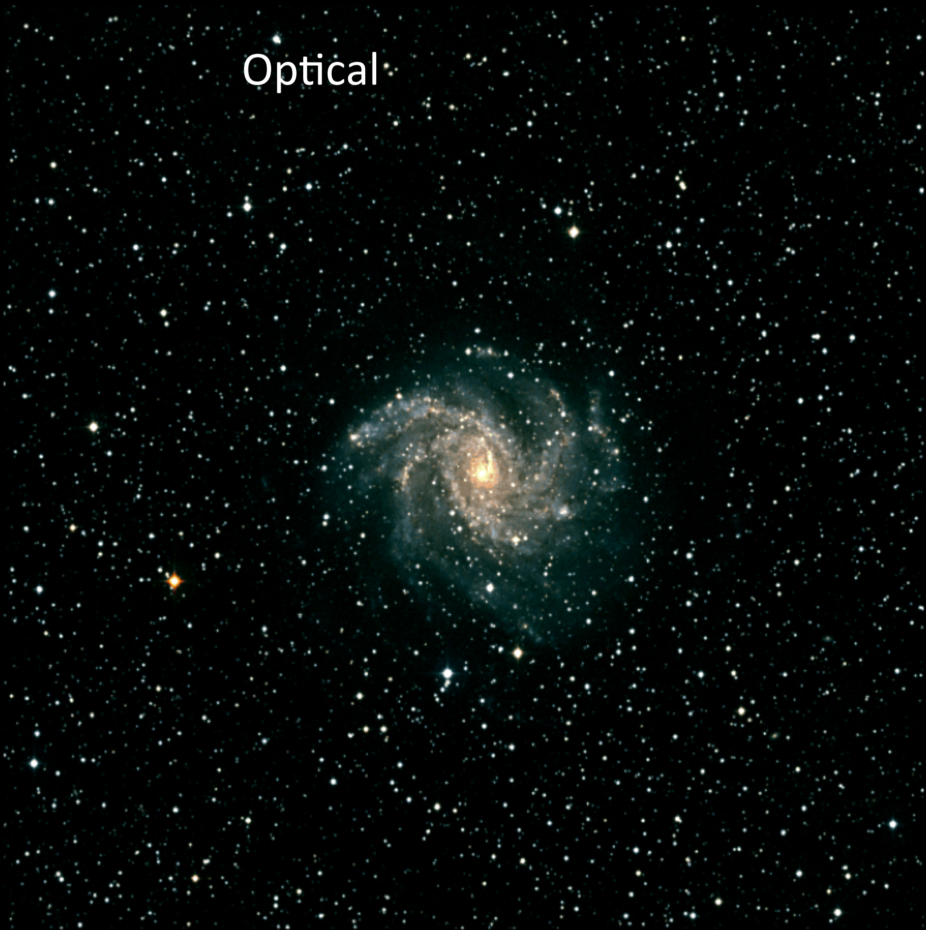
The star formation quenching mechanism traced by HI in Phoenix

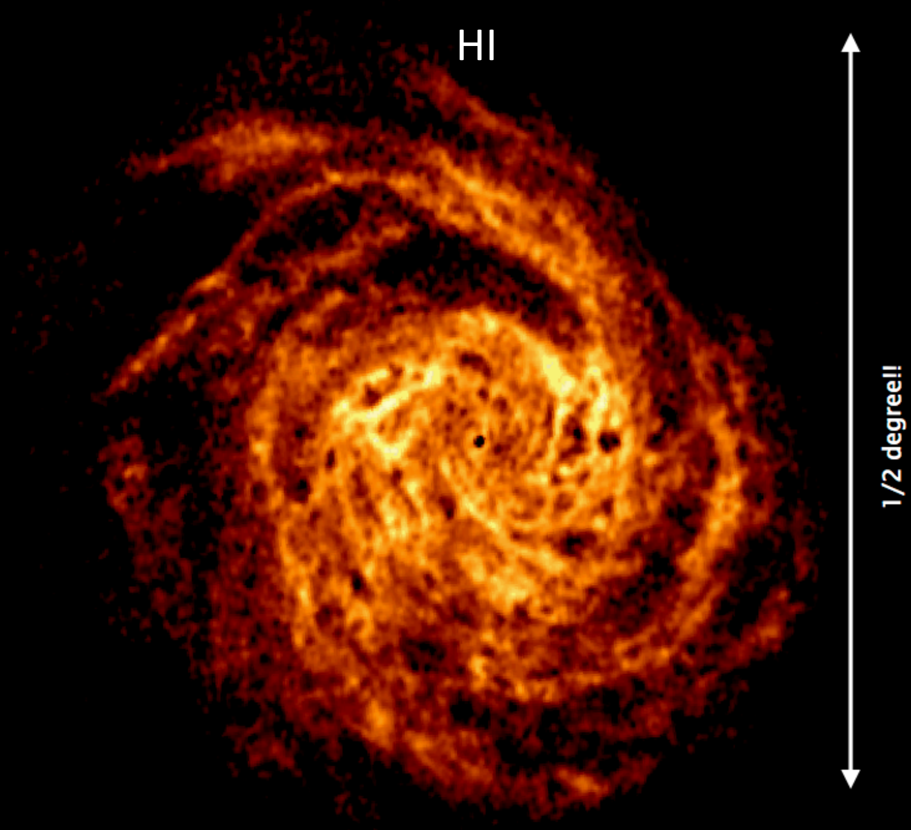


HI contours on top of the optical image

(Credit: LVHIS)

The optical and HI view of a galaxy

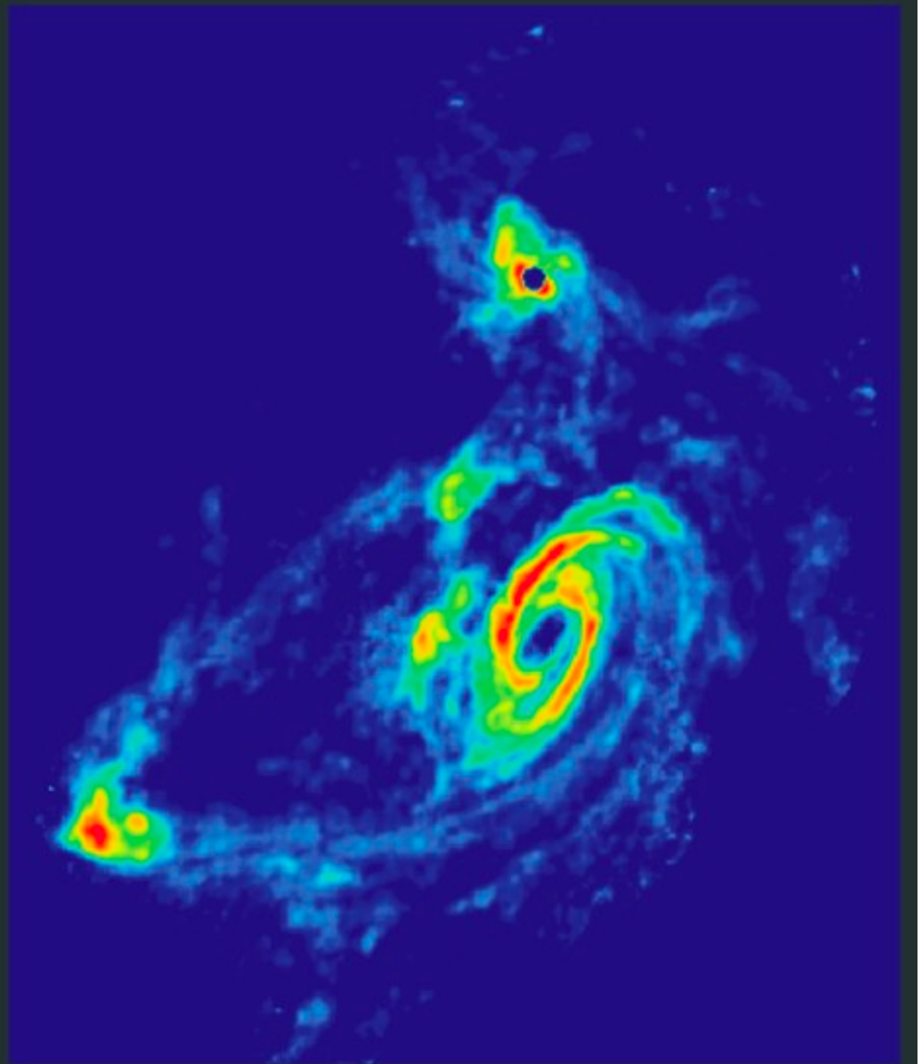




NGC 6946

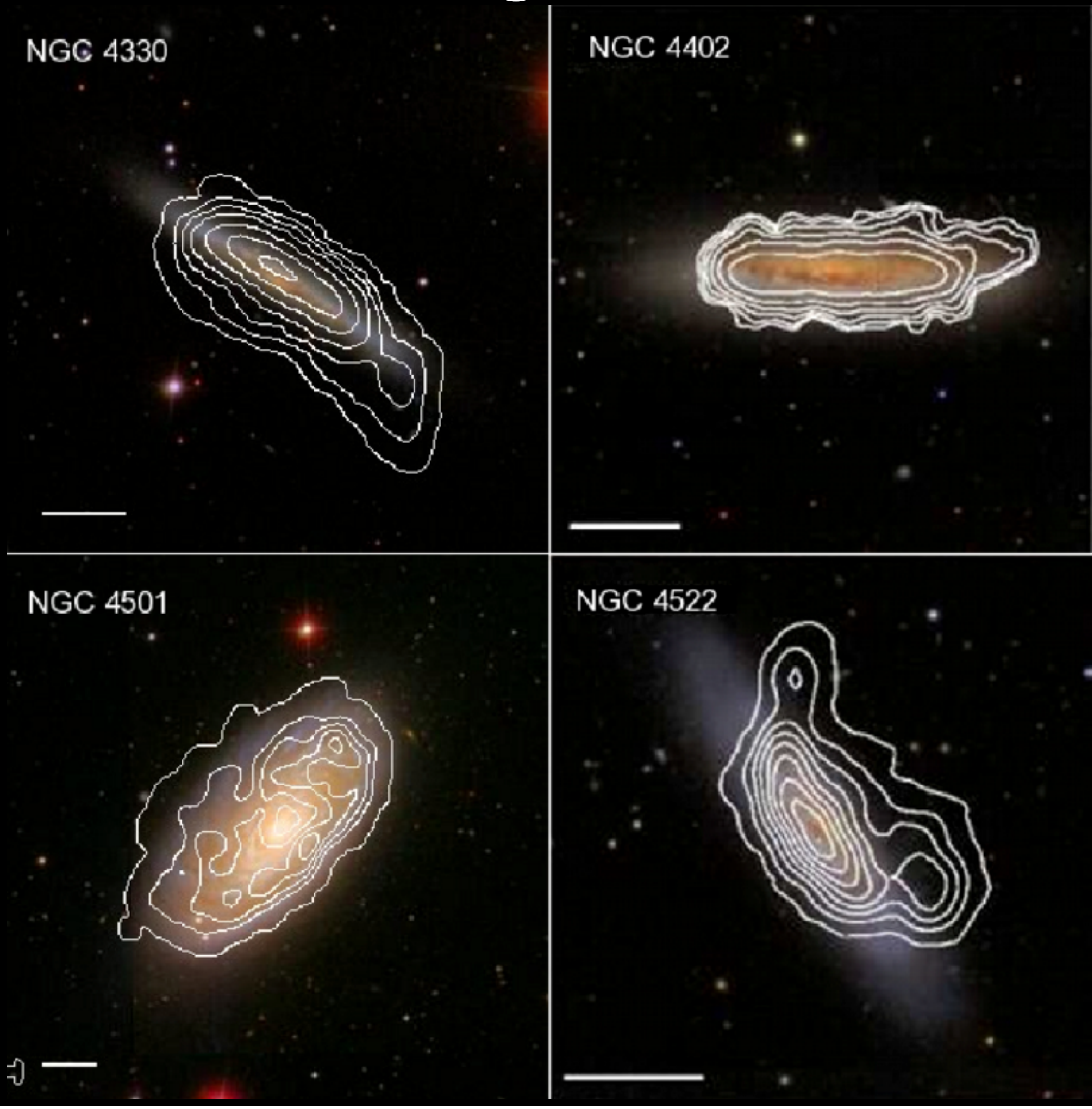
(Credit: T. Oosterloo)

Tidal stripping traced by HI in M 81 Group



(credit: NROA)

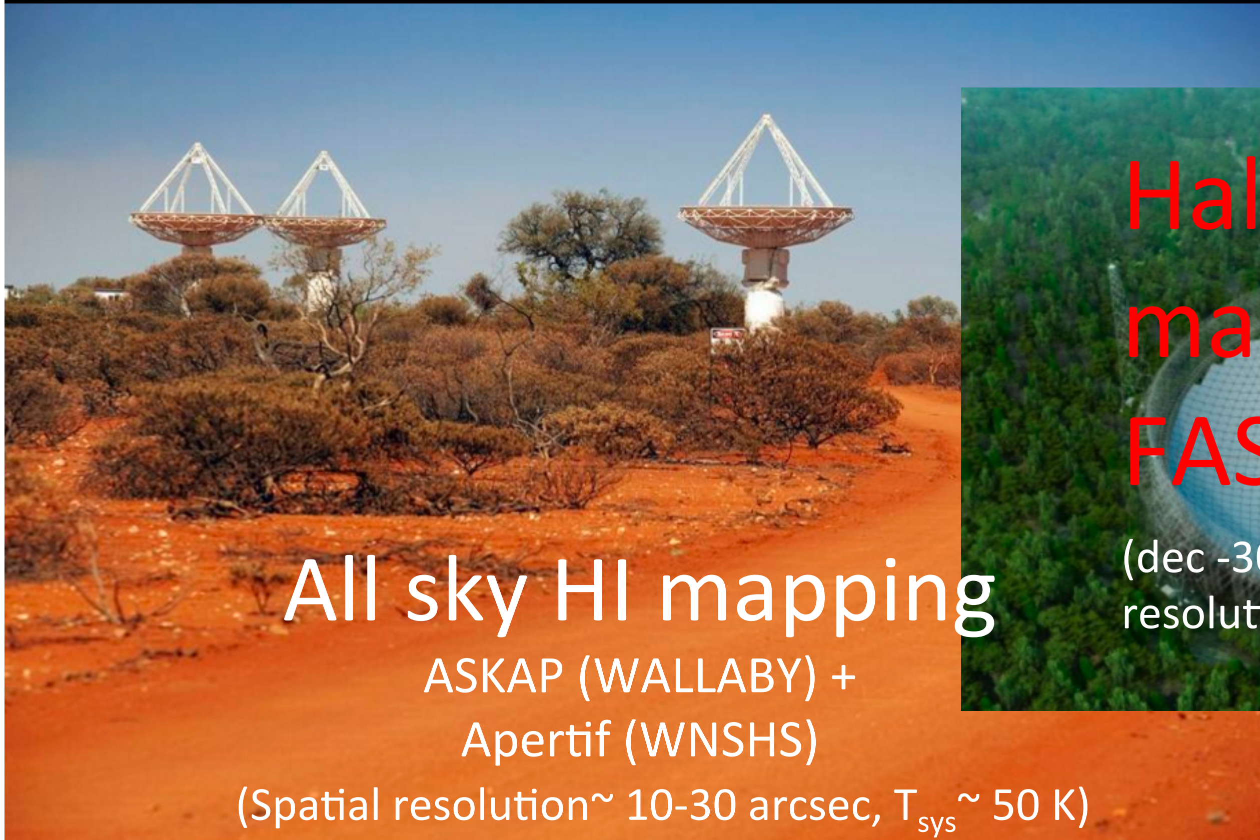
Ram pressure stripping traced by HI in the Virgo Cluster



(Credit: A. Chung)

Coming HI surveys defined at new/ upgraded HI facilities

- WALLABY (ASKAP): 2/3 sky HI survey
- WNSHS (WSRT, Apertif): 1/3 sky HI survey
- FLASH (ASKAP): HI absorption survey
- DINGO(ASKAP): deep HI for the GAMA field
- LADUMA (MeerKAT): deep HI for the ECDF-S field
- MONGHOOSE (MeerKAT): deep HI centered on selected galaxies
- Etc…



All sky HI mapping

ASKAP (WALLABY) +
Apertif (WNSHS)
(Spatial resolution~ 10-30 arcsec, T_{sys}~ 50 K)

Half sky HI mapping with FAST ?

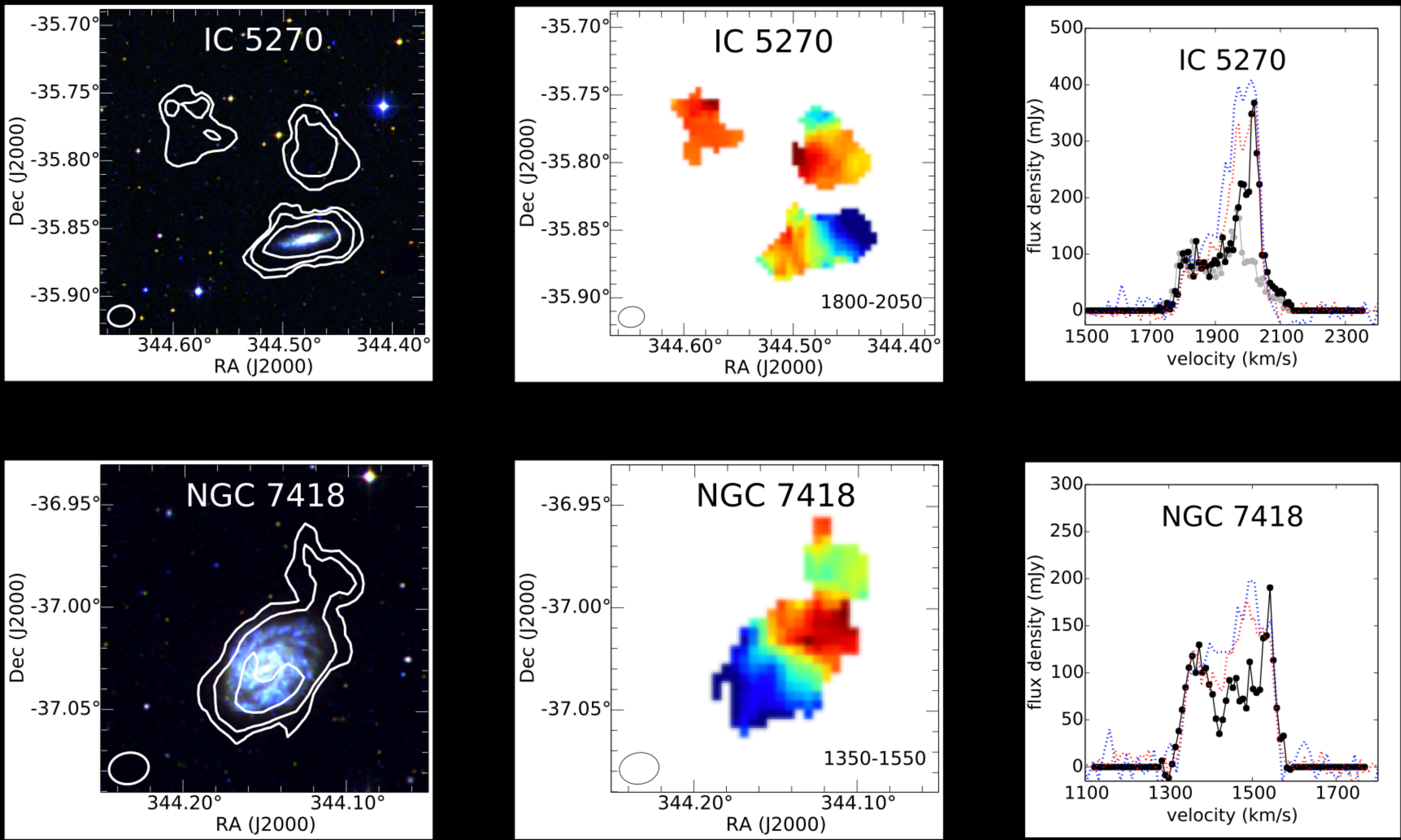
(dec -30~80 deg sky, spatial resolution~ 3 arcmin, T_{sys}~ 20 K)

$$\theta = 1.220\frac{\lambda}{D}$$

θ is the **angular resolution** (radians),
λ is the wavelength of light,
and D is the diameter of the lens' aperture.

ASKAP (Apertifi) shortest baselines: 20 (36) m -> Largest structure detectable: 44 (24.5)’, or 12.7 (7.1)*(Dis/Mpc) [kpc]

Group IC 1459 at Dis=29 Mpc



10% of detected HI mass is outside galaxies in the extended group environment, Serra et al. (2015)

Outline

- How do galaxies obtain the HI gas?
- How is HI distributed in galaxies?
- How do galaxies form stars in HI-dominated regions?
- How is star formation quenched in galaxies?
- How do galaxies (trans-)form their structure with the cold gas?

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The Bluedisk project--the distribution, morphology, kinematics and environment of HI and the accompanied molecular gas, gas phase metallicity and star formation distribution in massive HI-rich and normal disk galaxies at low redshift

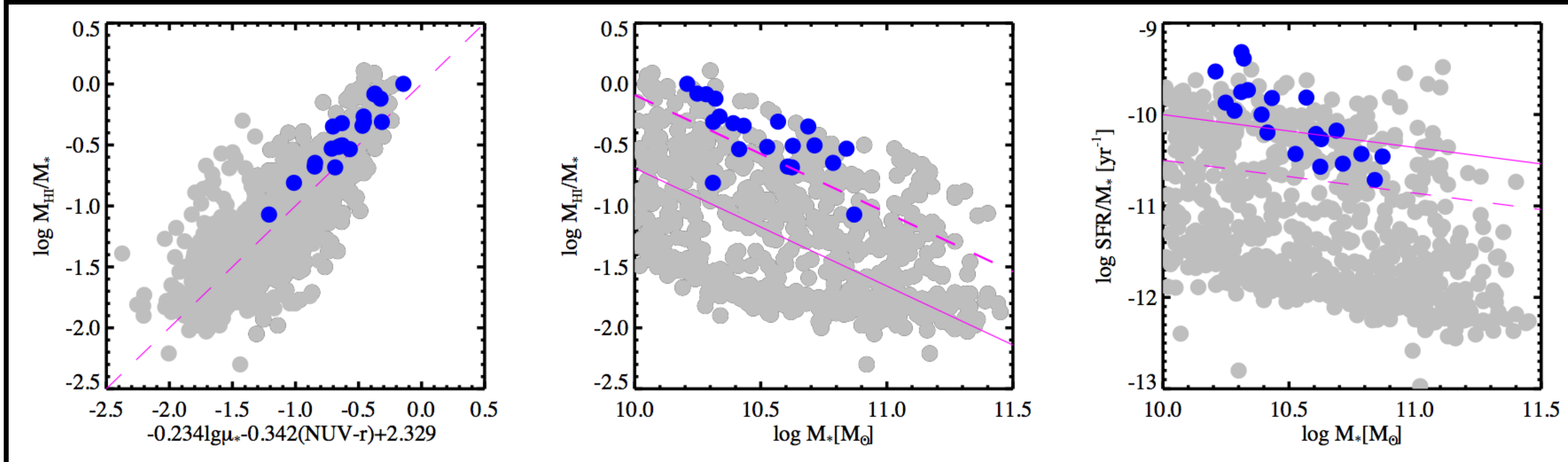
(Wang+13,14,15, E.Wang+15, der Heijen+15, Carton+15, Roychowdhury+15, Cormier in prep, Jozsa in prep)

FOOT PRINTS OF GAS ACCRETION

The Bluedisk project

PI: Guinevere Kauffmann (MPA)

- 20 massive HI-excess galaxies with log M*/M_sun~10-11, at z~0.023-0.03, with no major merge companions within 100 kpc.
- A control sample of another 20 HI-normal galaxies.



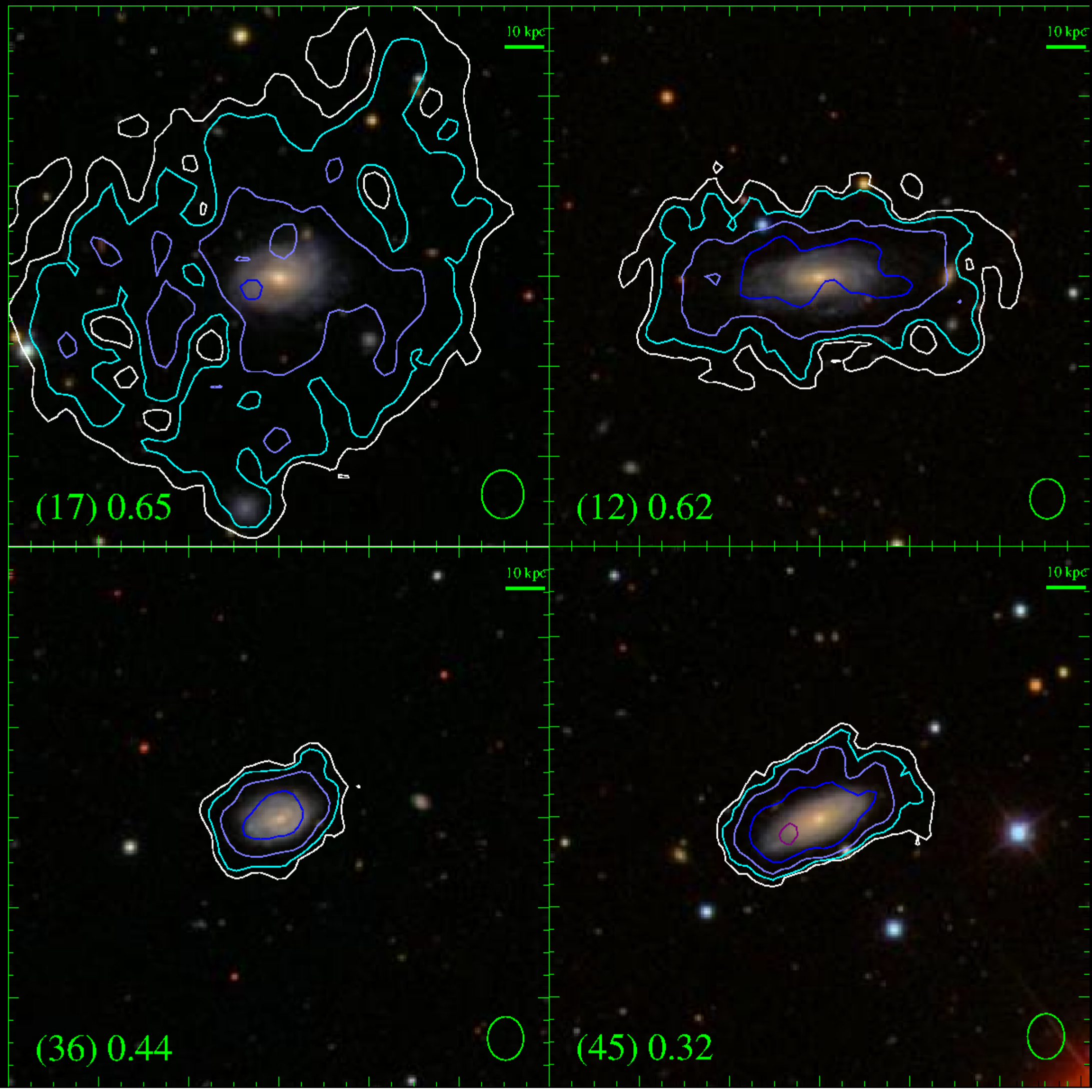
(Catinella+13 HI plane)

(Catinella+13 M*- M_{HI}/ M* relation)

(Schiminovich+07 SF sequence)

Wang+13,14

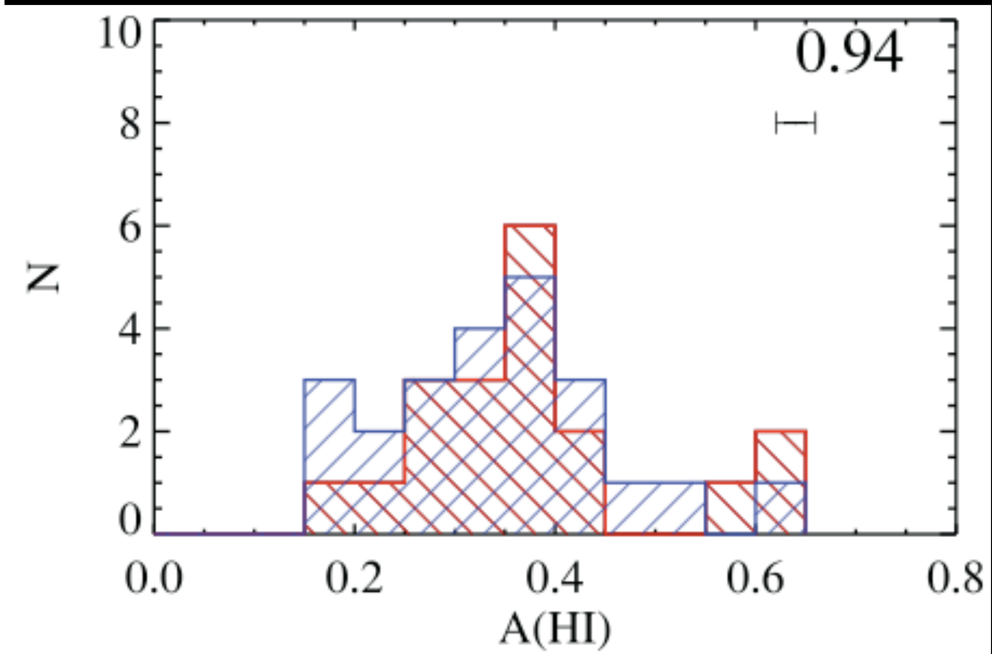
The Bluedisk synthesis HI data

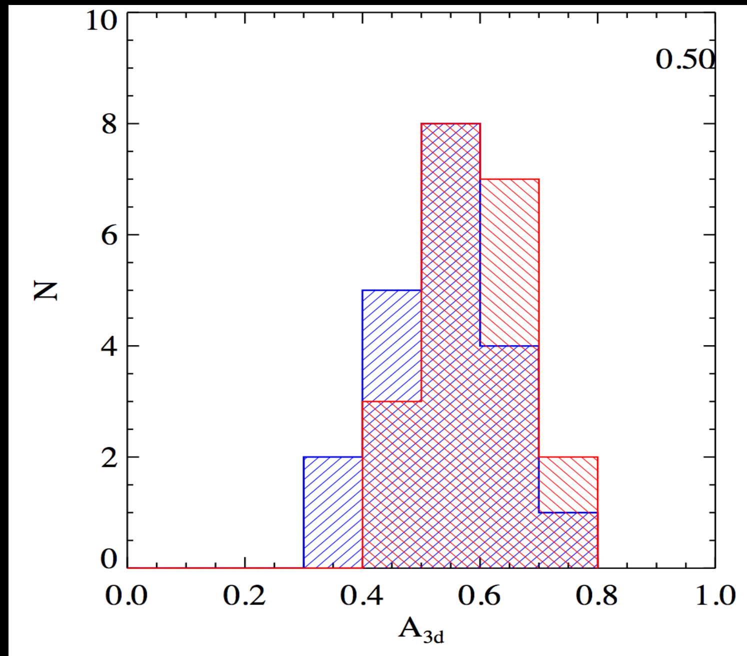


Westerbork observation
Resolution: 25 arcsec (10 kpc)
Depth:
  point sources~10^8 M_sun
  surface density ~$0.5*10^{20}$ cm^{-2}
Field-of-view: 1 deg (~2 Mpc)

http://www.mpa-garching.mpg.de/GASS/Bluedisk/index.php

HI in HI-excess galaxies show normal morphology





2D asymmetry

3D asymmetry

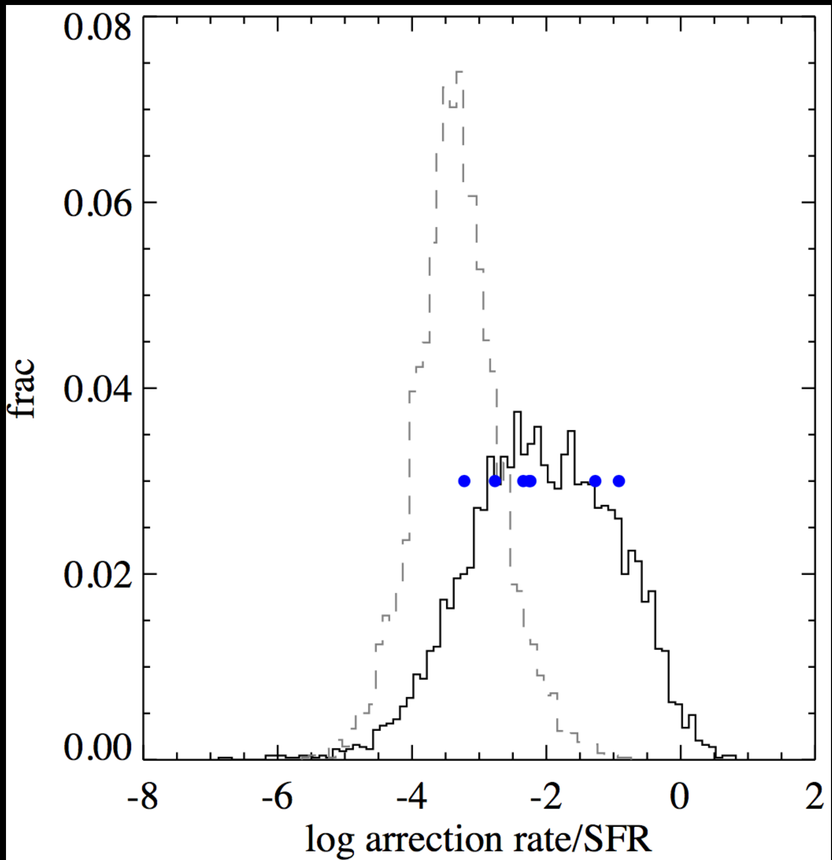
HI-excess

Control

No difference

Wang+13

Minor merger rate is too low to support SFR

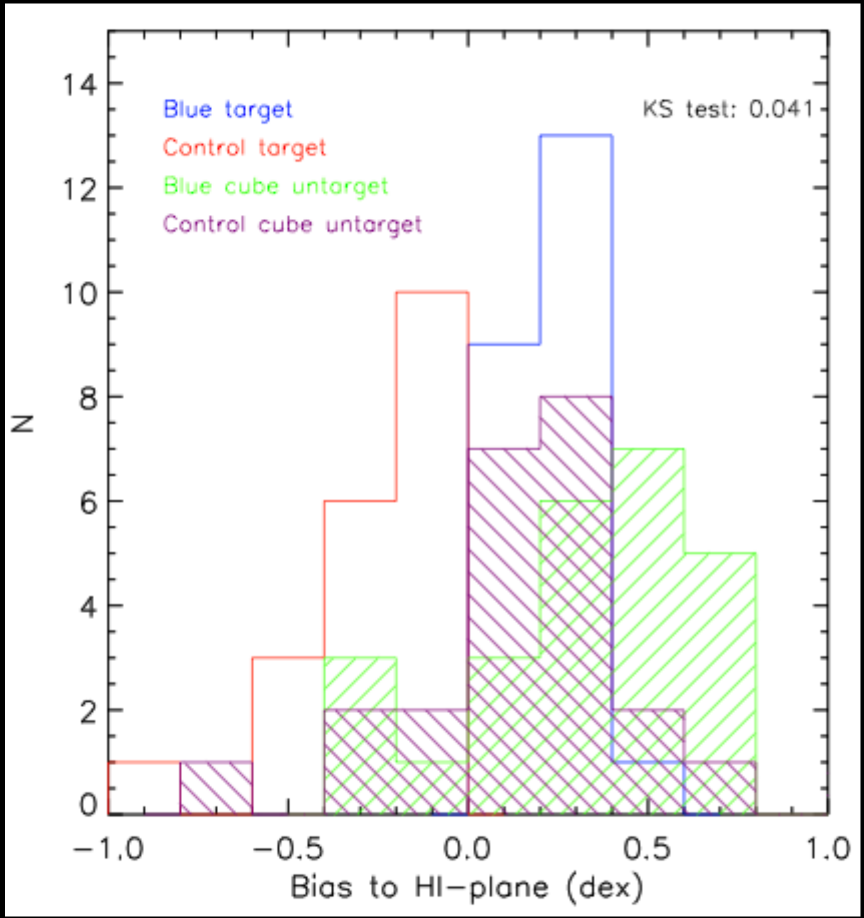


Among a sample of 20 HI-excess galaxies, only 8 of them have satellites with M_HI>10^8 M_sun, within a searching cylinder of 500 kpc and 500 km/s

Wang+ 15

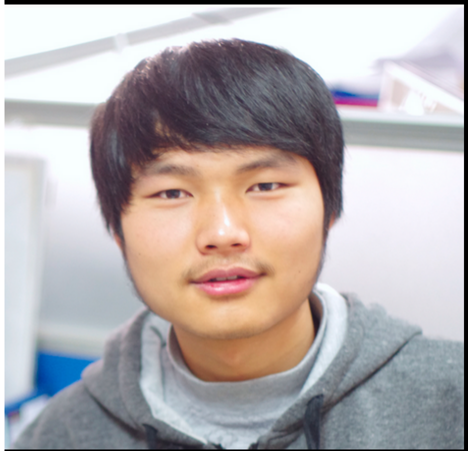
HI excess in centrals and satellites

HI-rich central
Control central
Satellites around HI-rich central
Satellites around control central



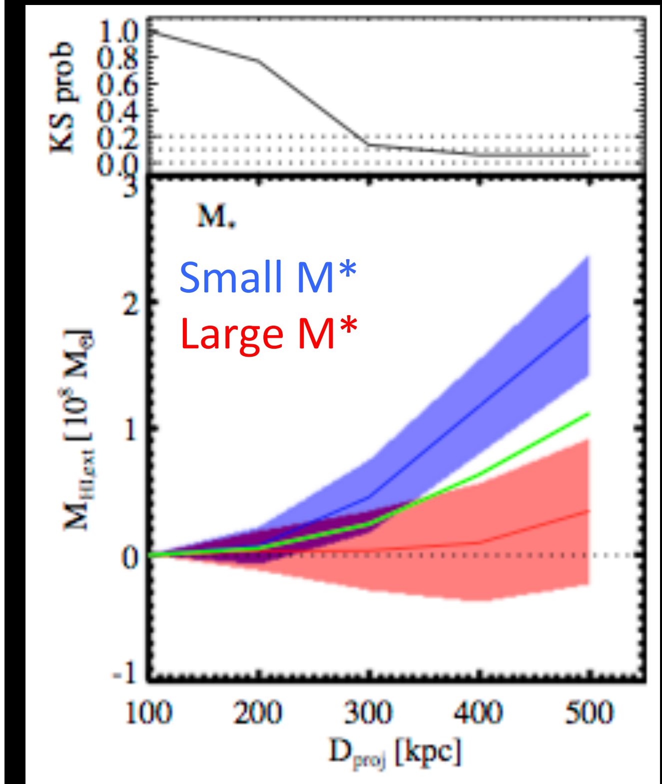
"The centrals and satellites might be fueled by a common underlying reservoir of cold gas" ,"possibly the cold-mode accretion predicted by simulations"
--Kauffmann et al. (2010)

Enci Wang (SHAO)

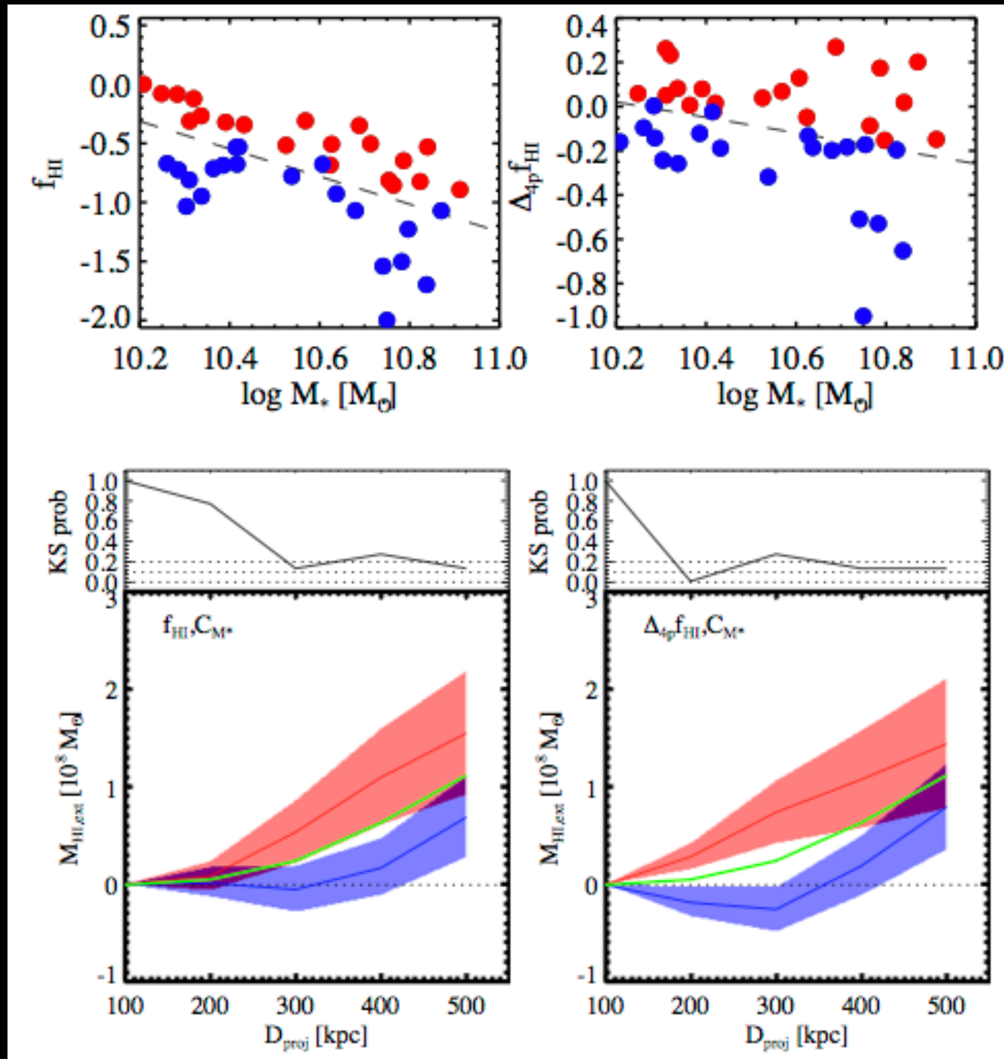


E. Wang+15

HI mass of undetected systems in the 1 Mpc environment



Wang+ 15



Accretion of cold gas in massive disk galaxies at low redshift

- is in a smooth and gentle way
- is not contributed much by merger events (major or minor)
- is connected with the HI present in the large-scale environment, possibly the cold-mode accretion predicted by CDM simulations

AKSAP may allow us to analyze the structure of the HI large scale environment, while FAST may reveal the iceberg below the detected tips

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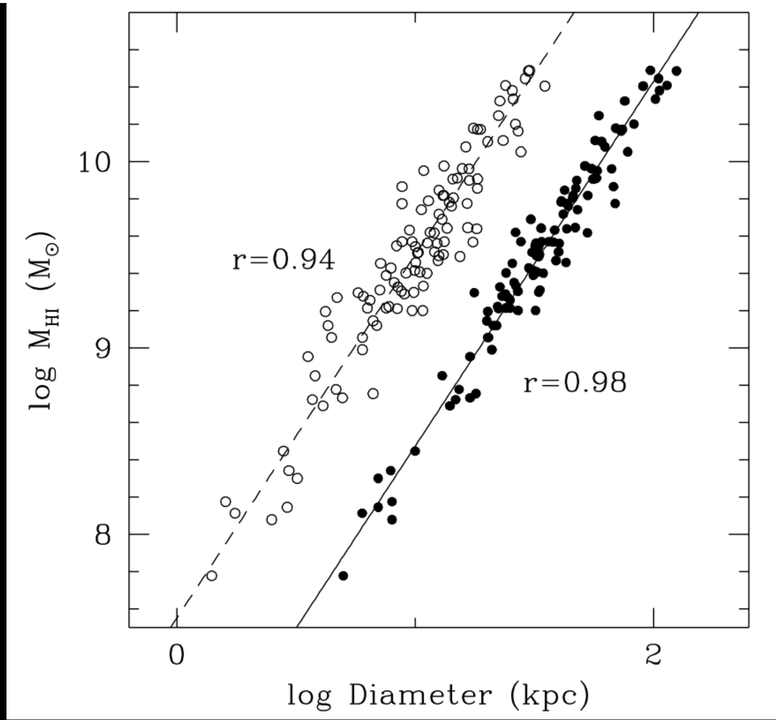
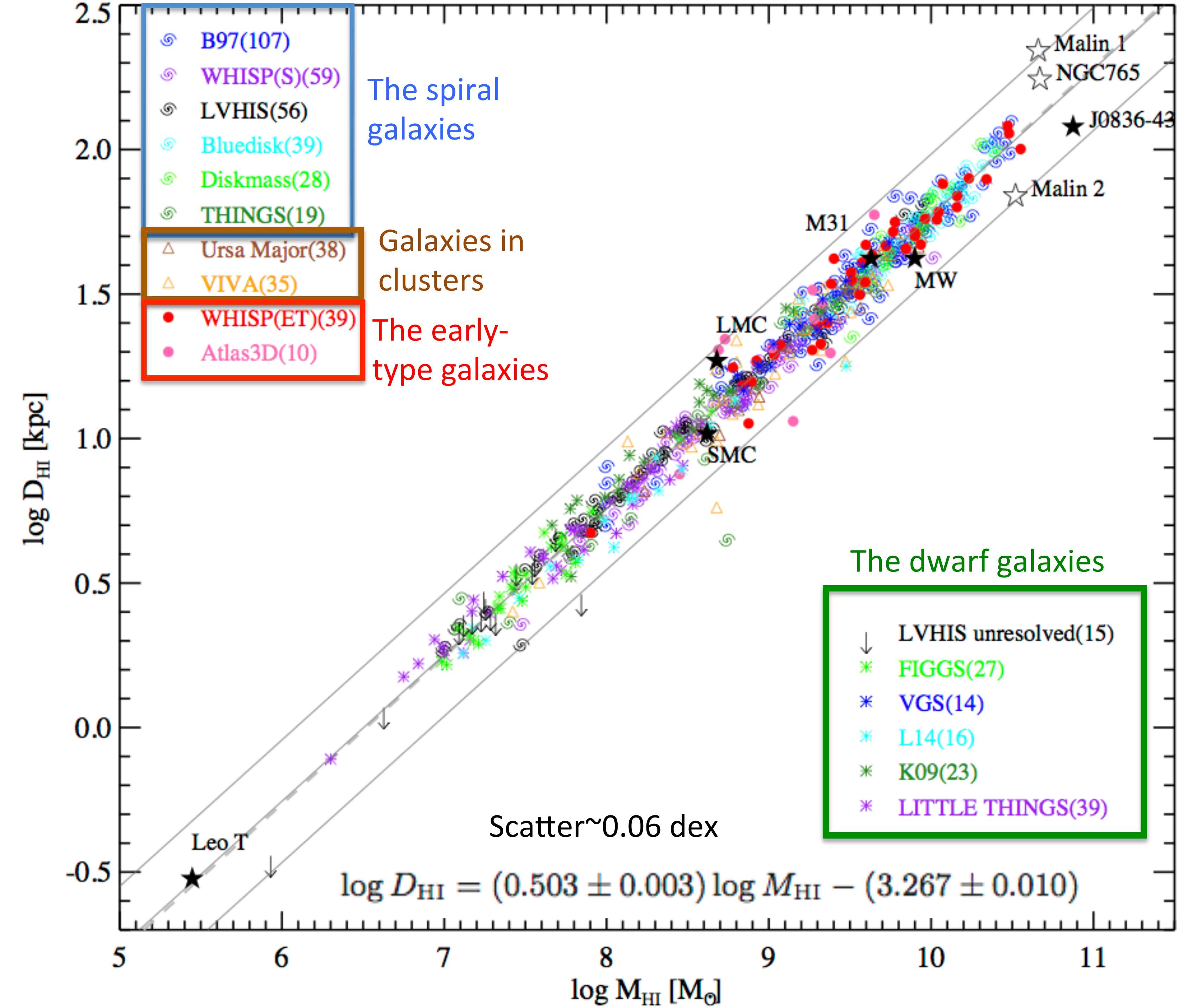


The Broeils relation

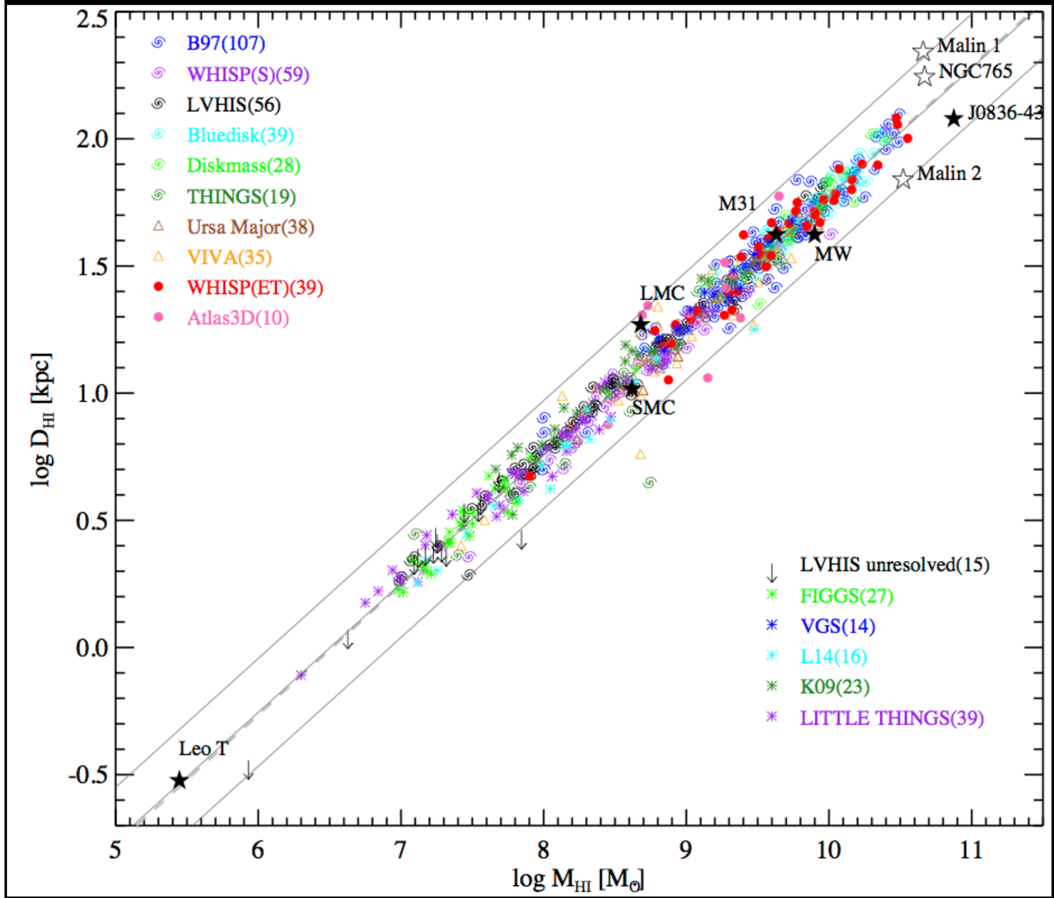
D_{HI}: major axis of 1 M_{sun} pc^{-2} isophot

New lessons from revisiting the HI size-mass relation of Broeils+97 (Wang+ submitted)

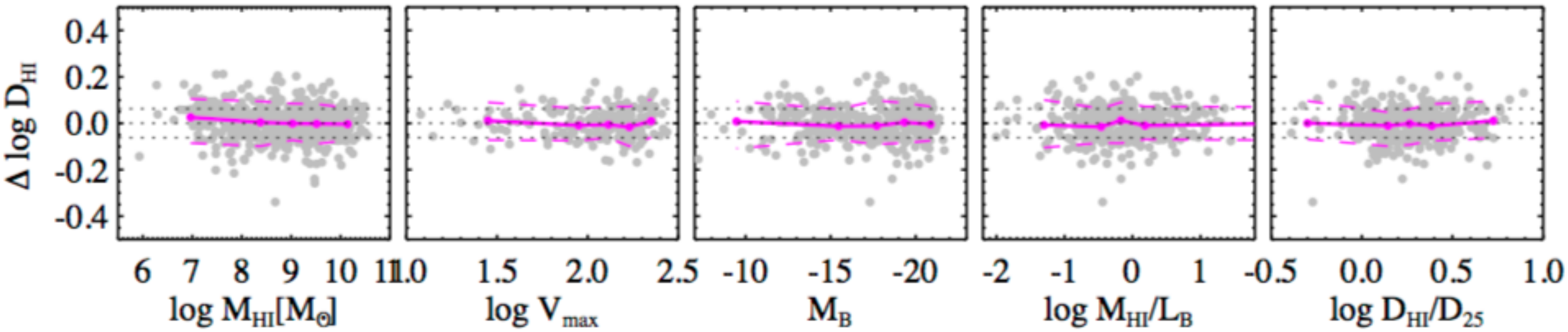
THE DISTRIBUTION OF HI IN GALAXIES



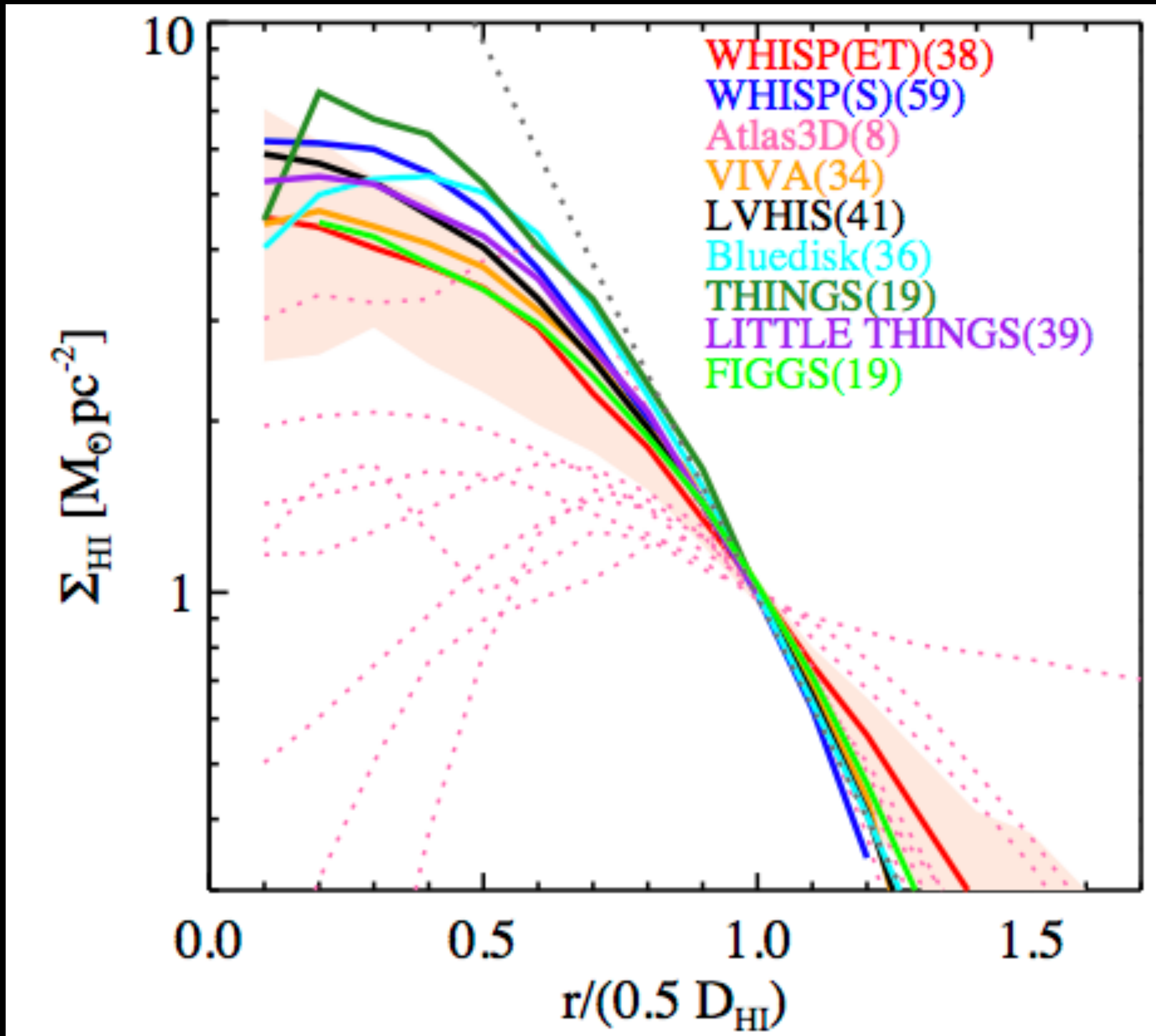
B97(107)
WHISP(S)(59)
LVHIS(56)
Bluedisk(39)
Diskmass(28)
THINGS(19)
The spiral galaxies
Ursa Major(38)
VIVA(35)
Galaxies in clusters
WHISP(ET)(39)
Atlas3D(10)
The early-type galaxies
Malin 1
NGC765
J0836-43
Malin 2
M31
MW
LMC
SMC
Leo T
The dwarf galaxies
LVHIS unresolved(15)
FIGGS(27)
VGS(14)
L14(16)
K09(23)
LITTLE THINGS(39)
Scatter~0.06 dex
$\log D_{HI} = (0.503 \pm 0.003) \log M_{HI} - (3.267 \pm 0.010)$
log D_{HI} [kpc]
log M_{HI} [$M_\odot$]



Challenges to theoretical models



Clues from the radial distribution of HI



Indication of scaling relation between the masses of HI and dark matter

$$m_{HI} = M_{HI}/M_{halo}$$

$$\text{const.} \propto M_{HI}/R_{HI}^2 \propto m_{HI} M_{halo}/R_{halo}^2 \propto m_{HI} M_{halo}^{1/3}$$

So, $$M_{HI}/M_{halo} \propto M_{halo}^{-1/3}$$ (This work)

$$M_*/M_{halo} \propto M_{halo}^{0.54}$$ (from optical size-stellar mass relation, Kauffmann et al. 2003)

- The low efficiency of locking baryon mass in stars in small halos is because the efficiency of converting cold gas to stars is low, not because the halos are devoid of cold gas. (The missing baryon problem?)

- Combining the two scalings:

$$M_{HI}/M_* \propto M_{halo}^{-0.87} \propto M_*^{-0.53}$$

Consistent with the stellar mass limited HI survey for massive galaxies (GASS , Catinella+10).

The new lessons:

- Galaxies of different types lie on the same D_{HI}-M_{HI} relation; the scatter of the relation does not depend on the mass, HI richness or HI-to-optical size ratio of the galaxies

More clues may come from kinematic analysis of HI from future high resolution images (MeerKat, EVLA, SKA..)

- The slope of the relation predicts a scaling relation between HI mass and stellar mass.

This is going to be tested by future optically defined HI mass surveys (FAST telescope?)

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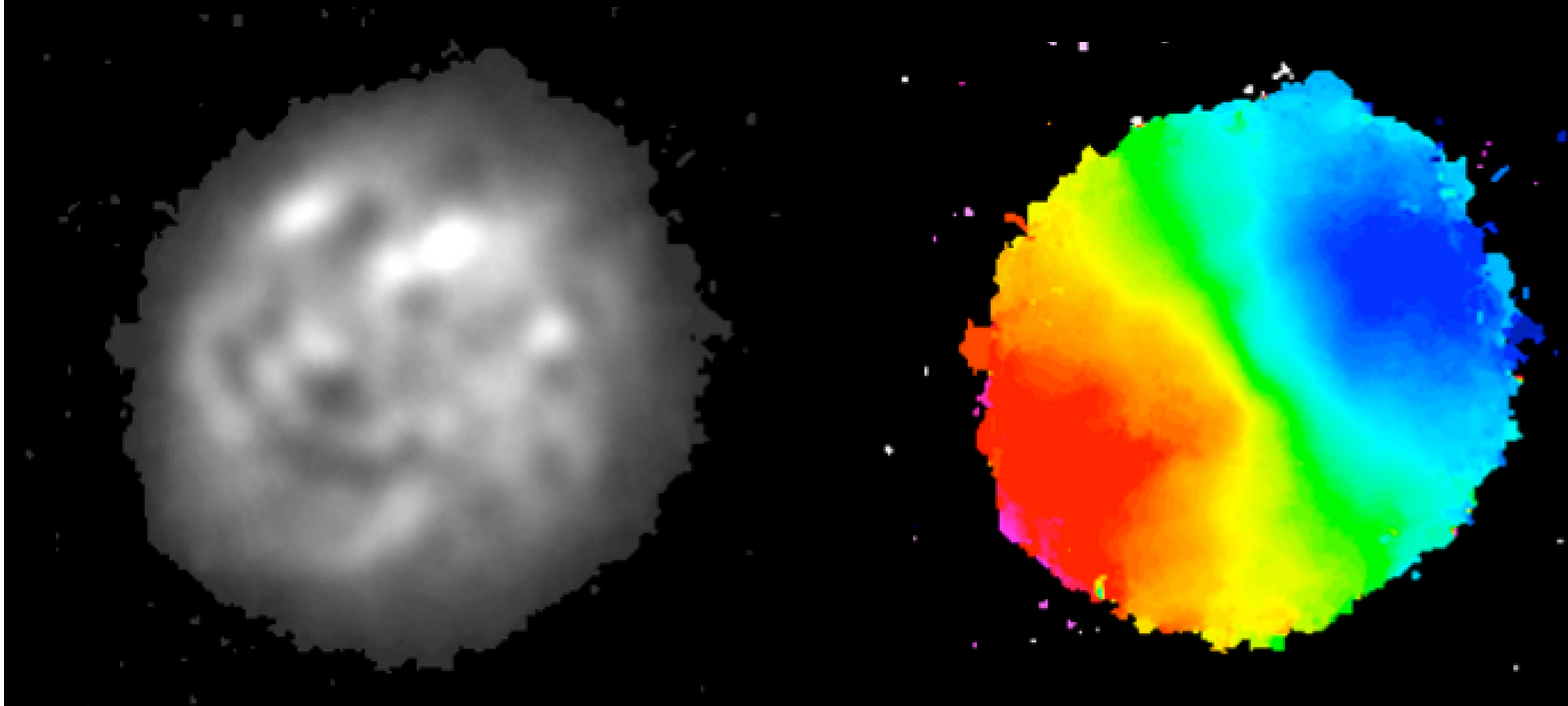
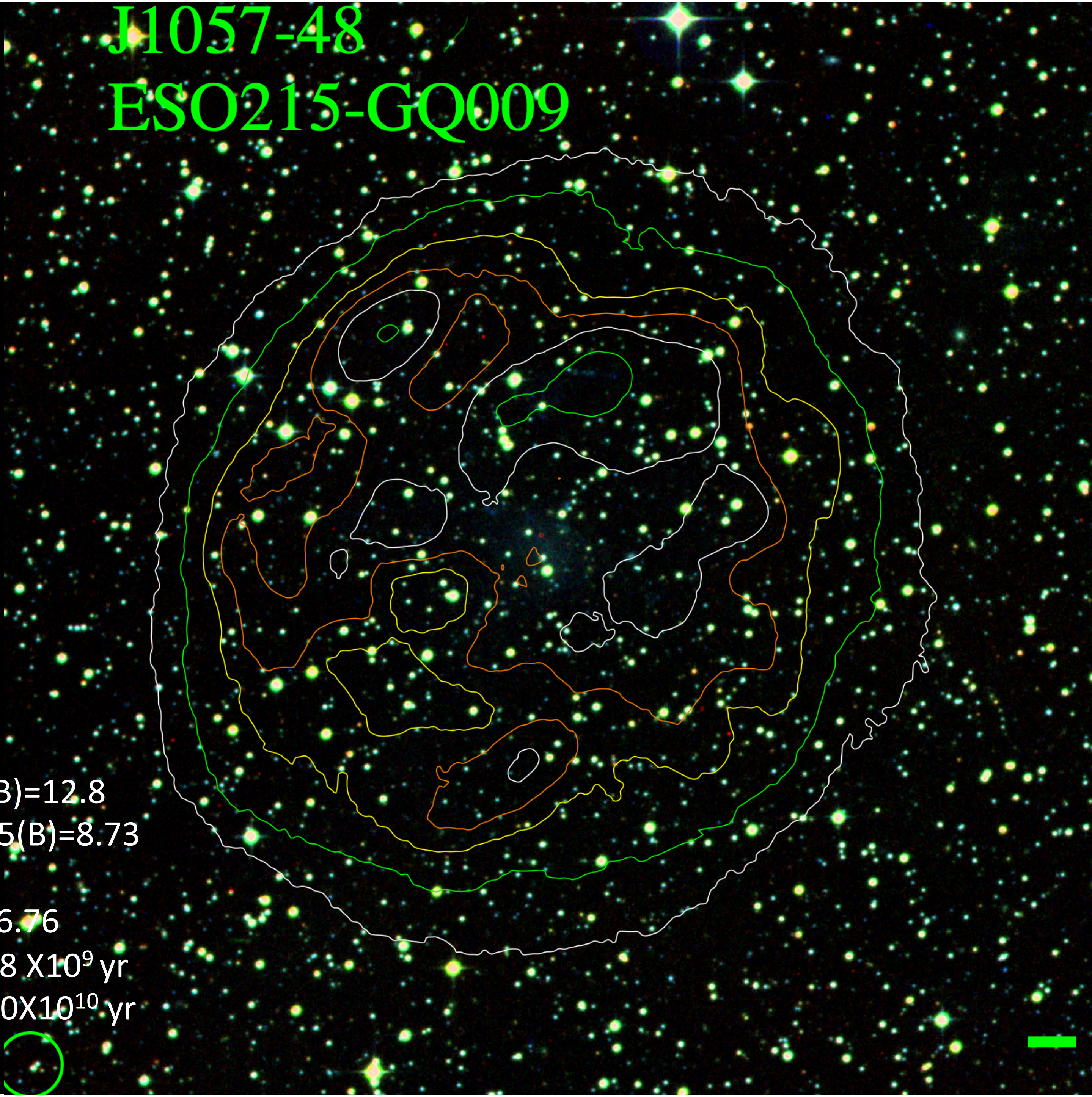
A case study of the dwarf galaxy ESO215-G?009

(Koribalski & Wang in prep)

STAR FORMATION IN HI-DOMINATED REGIONS

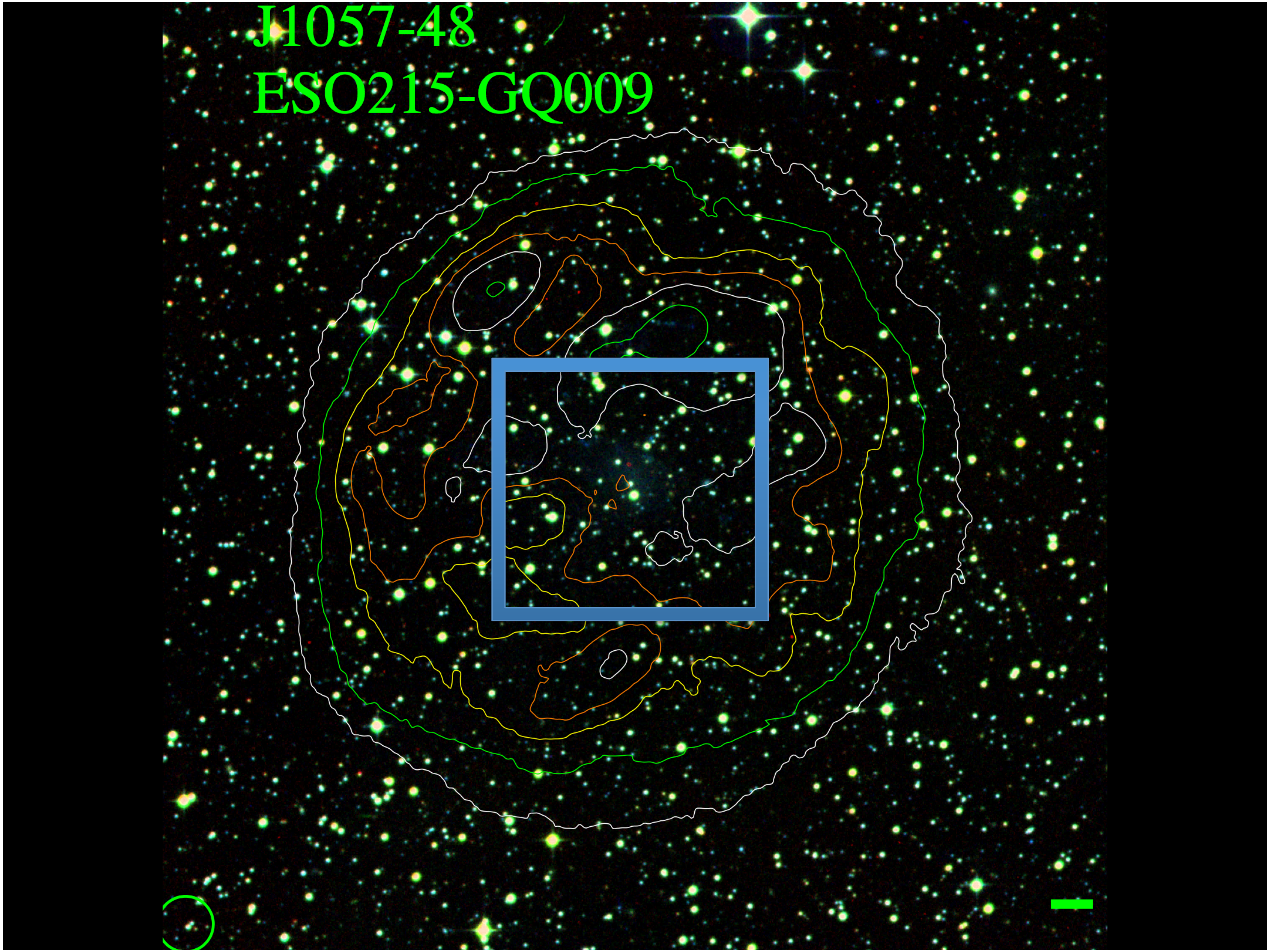
HI disk of ESO215-G?009

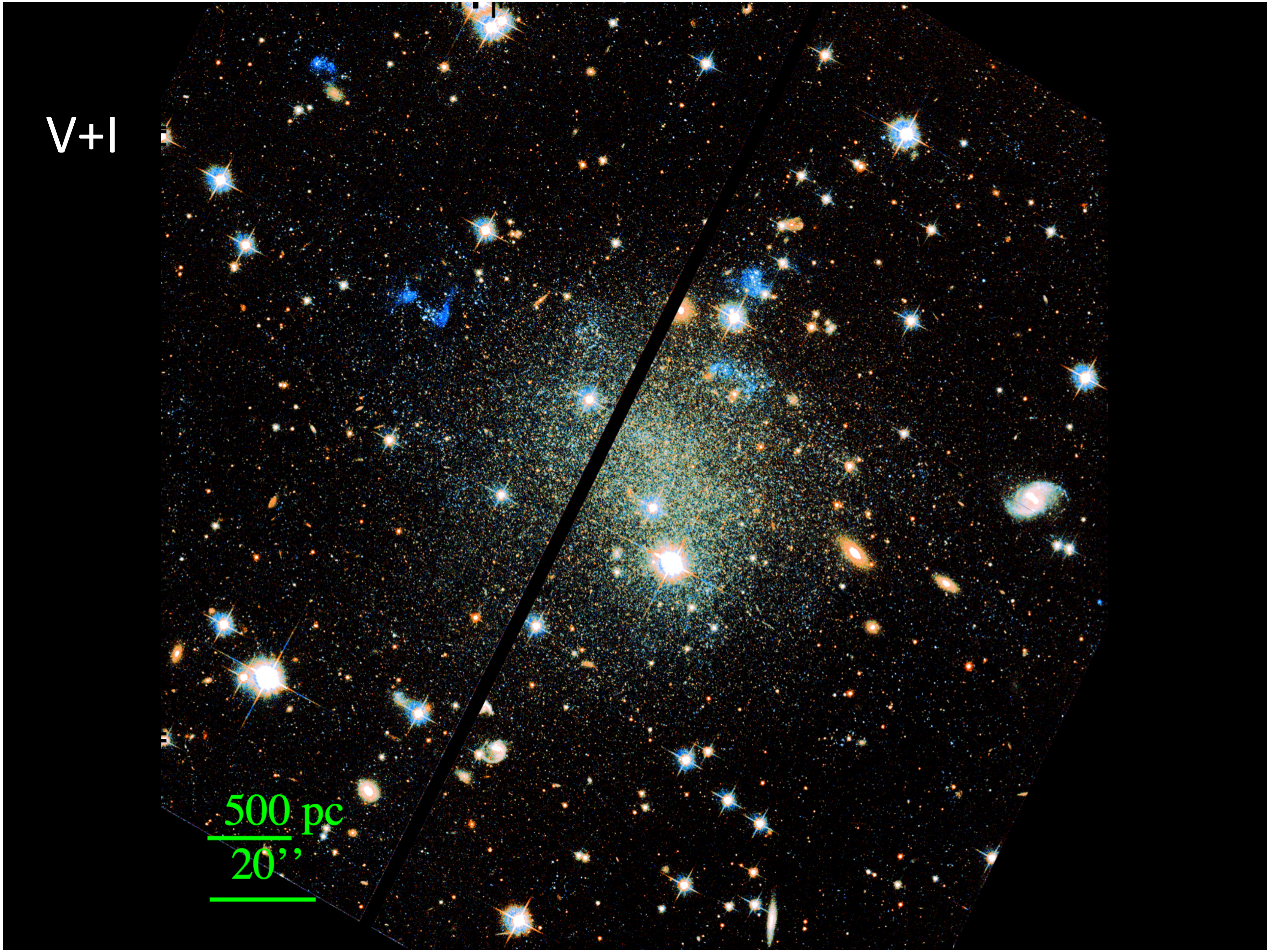


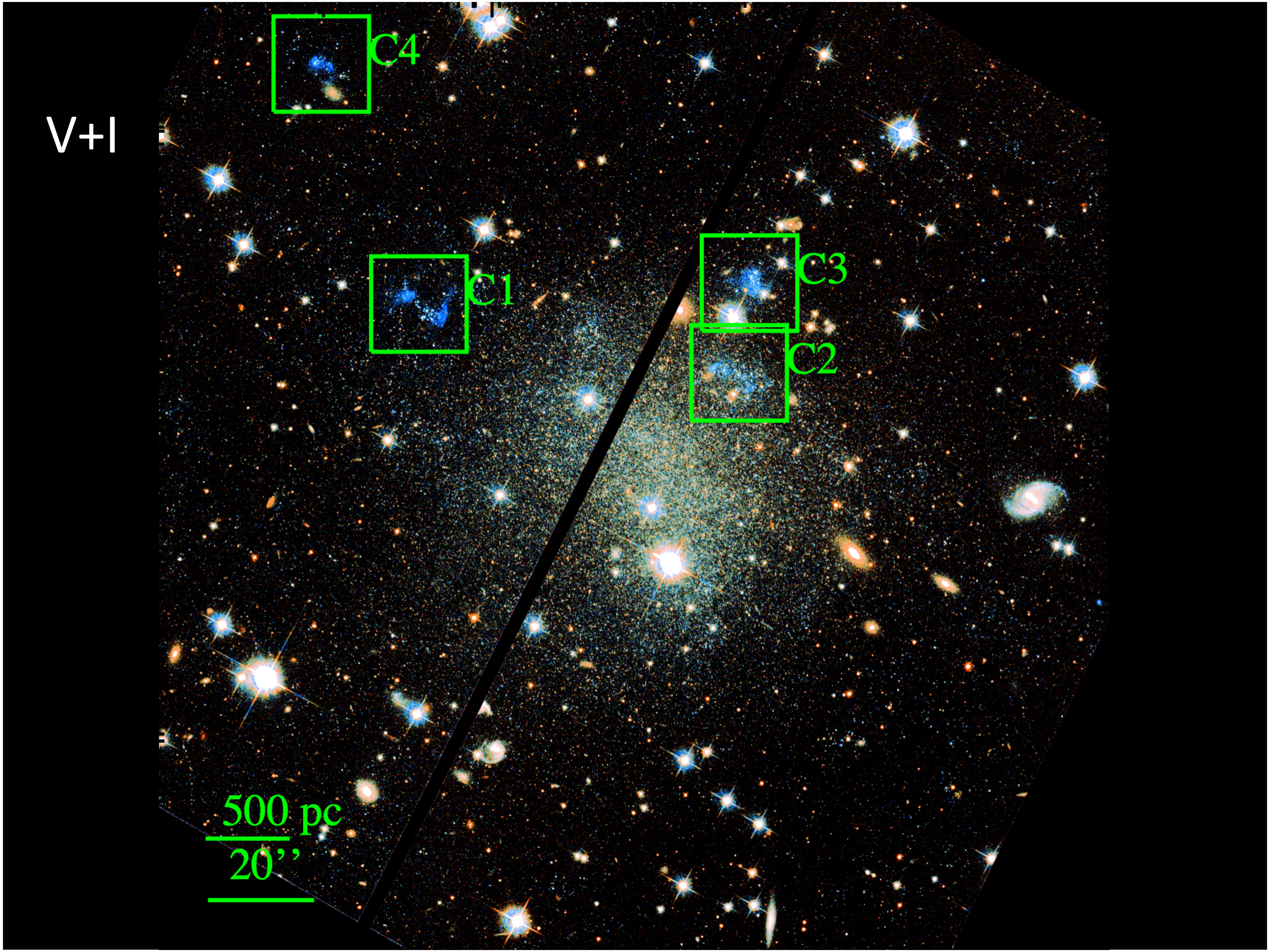


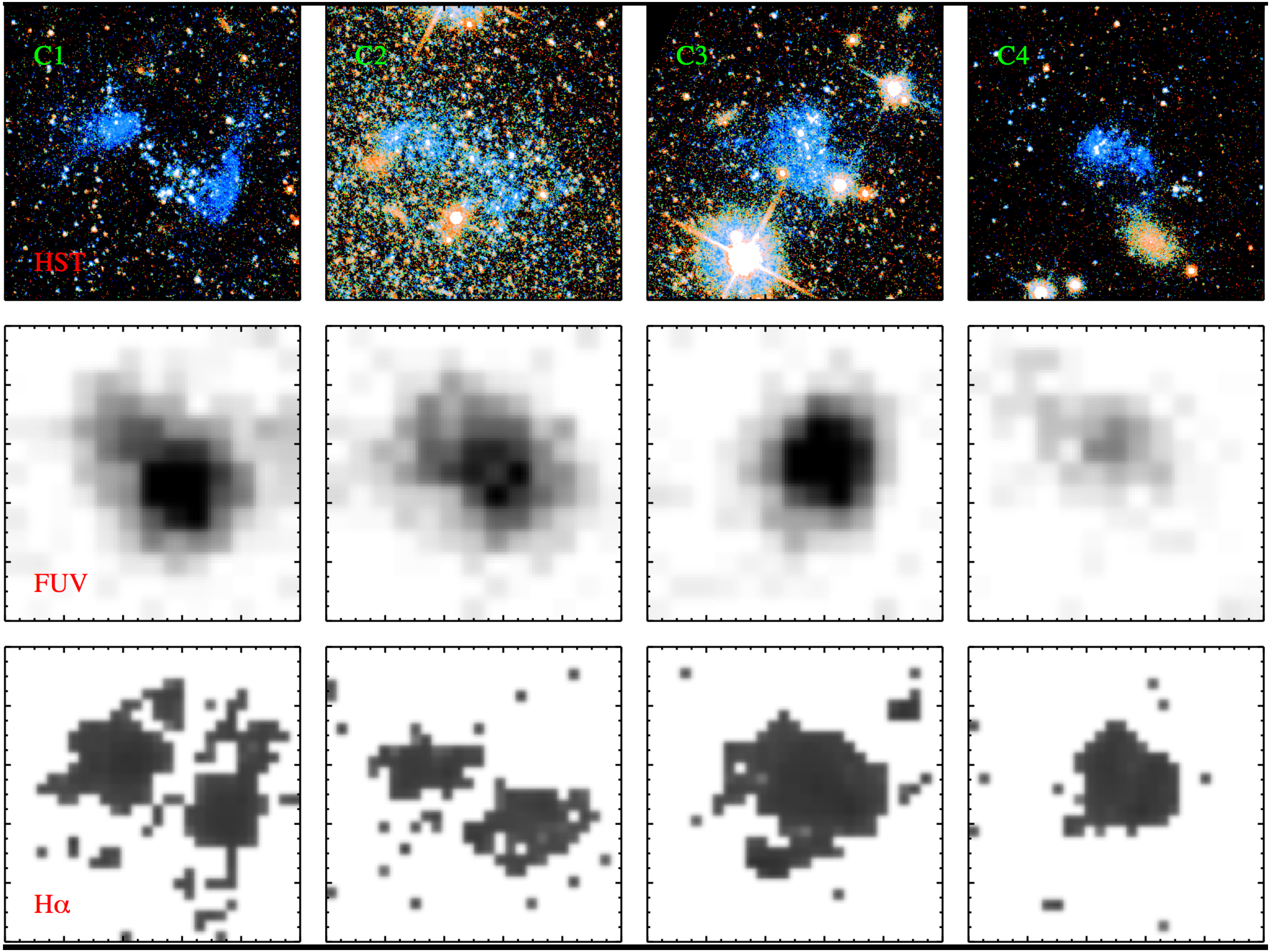
R05(HI)/r_s(B)=12.8
R05(HI)/R25(B)=8.73

M(HI)/M_*~6.76
M_*/SFR ~5.8 X10^9 yr
M_{HI}/SFR~4.0X10^{10} yr


J1057-48
ESO215-GQ009

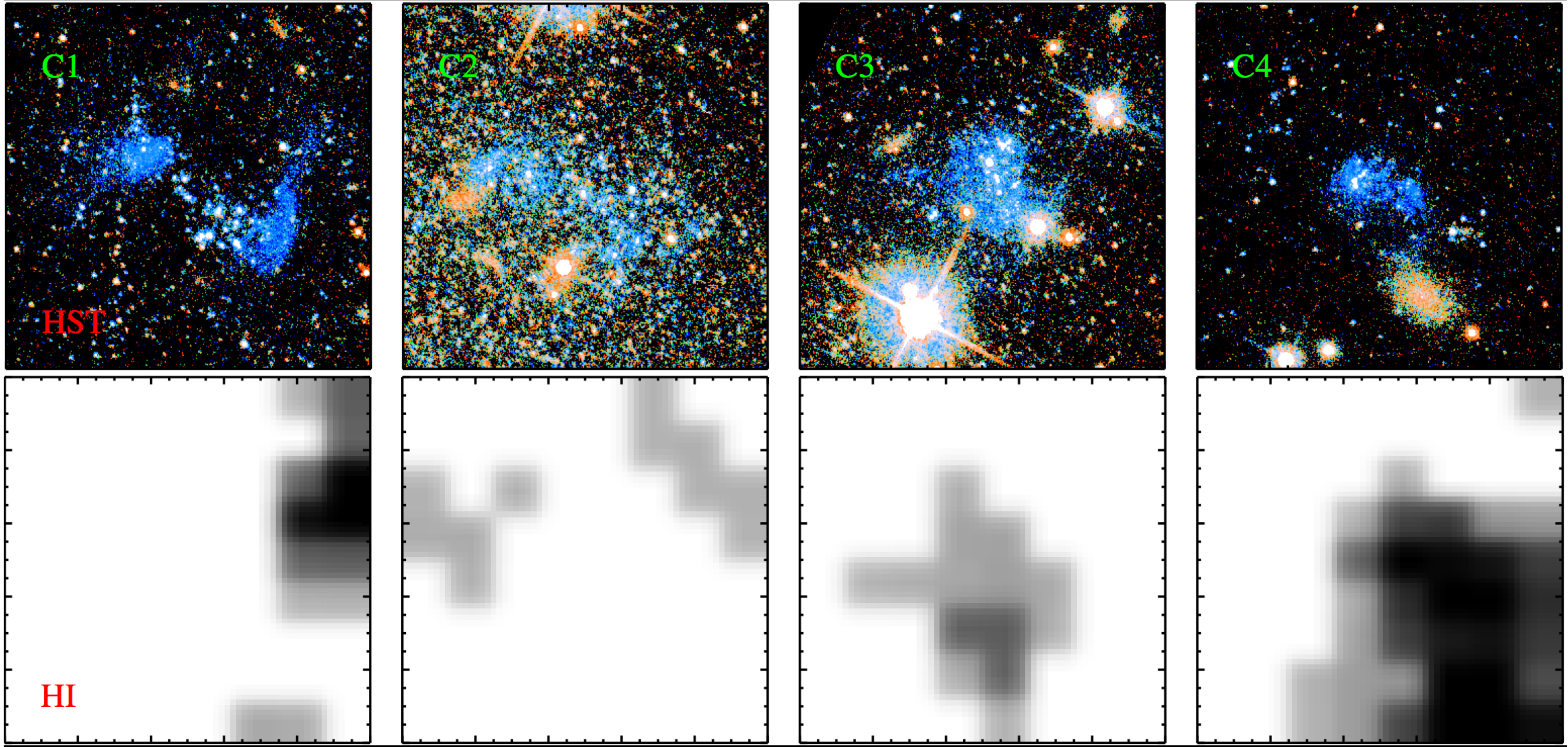

V+I
500 pc
20''


V+I
C4
C1
C3
C2
500 pc
20''



C1
C2
C3
C4
HST
FUV
Hα

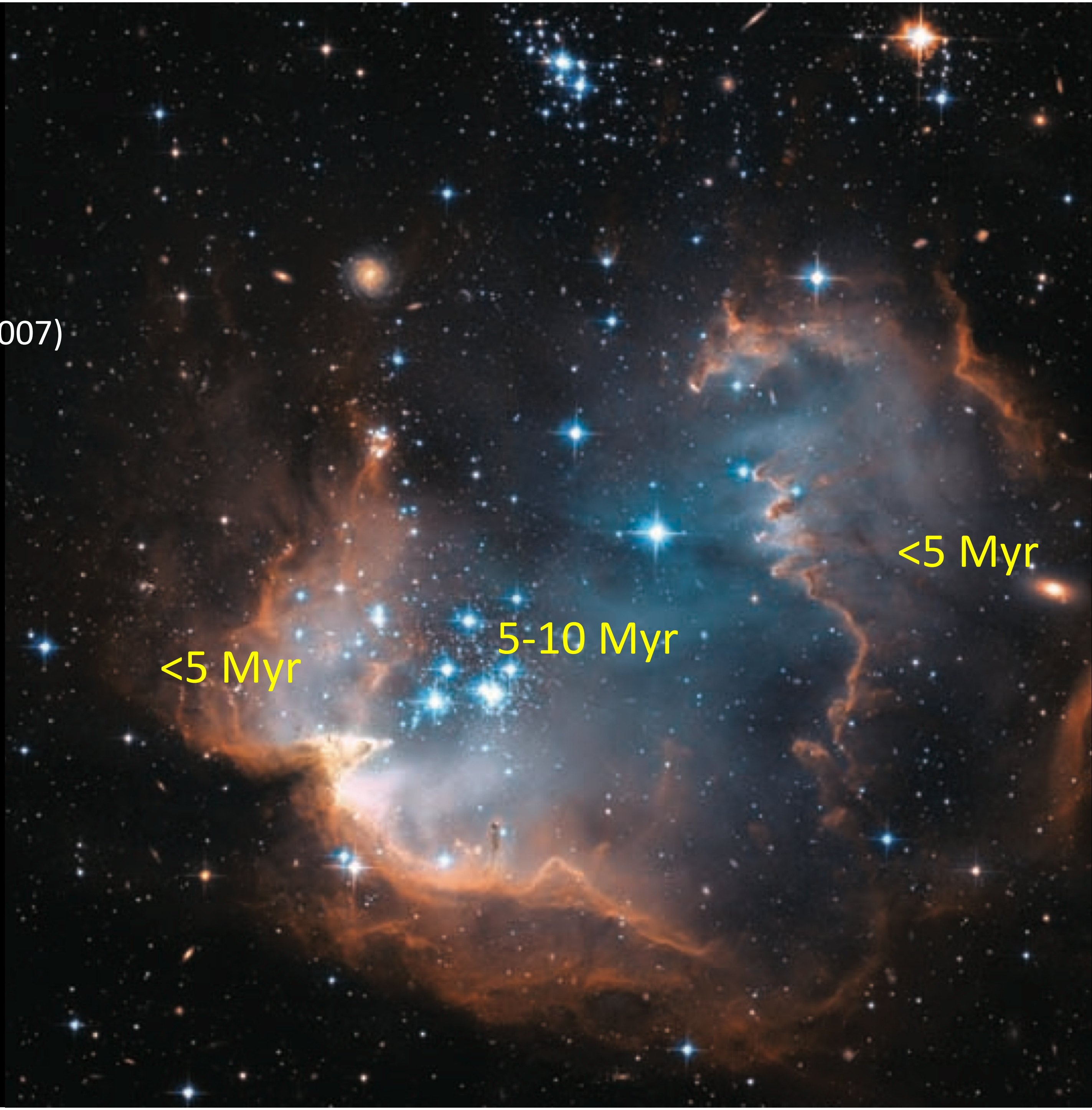
Lack of corresponding HI peaks

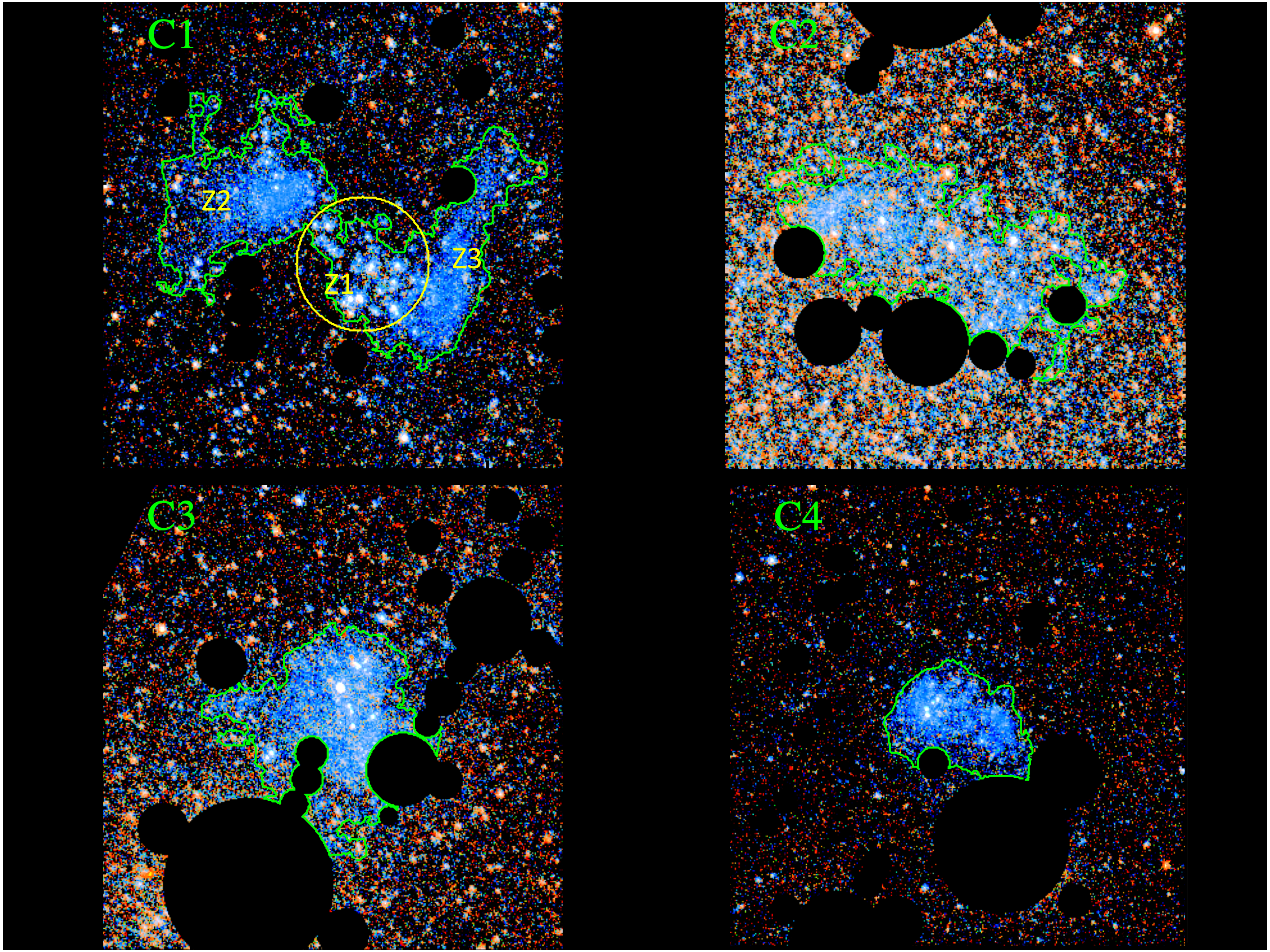


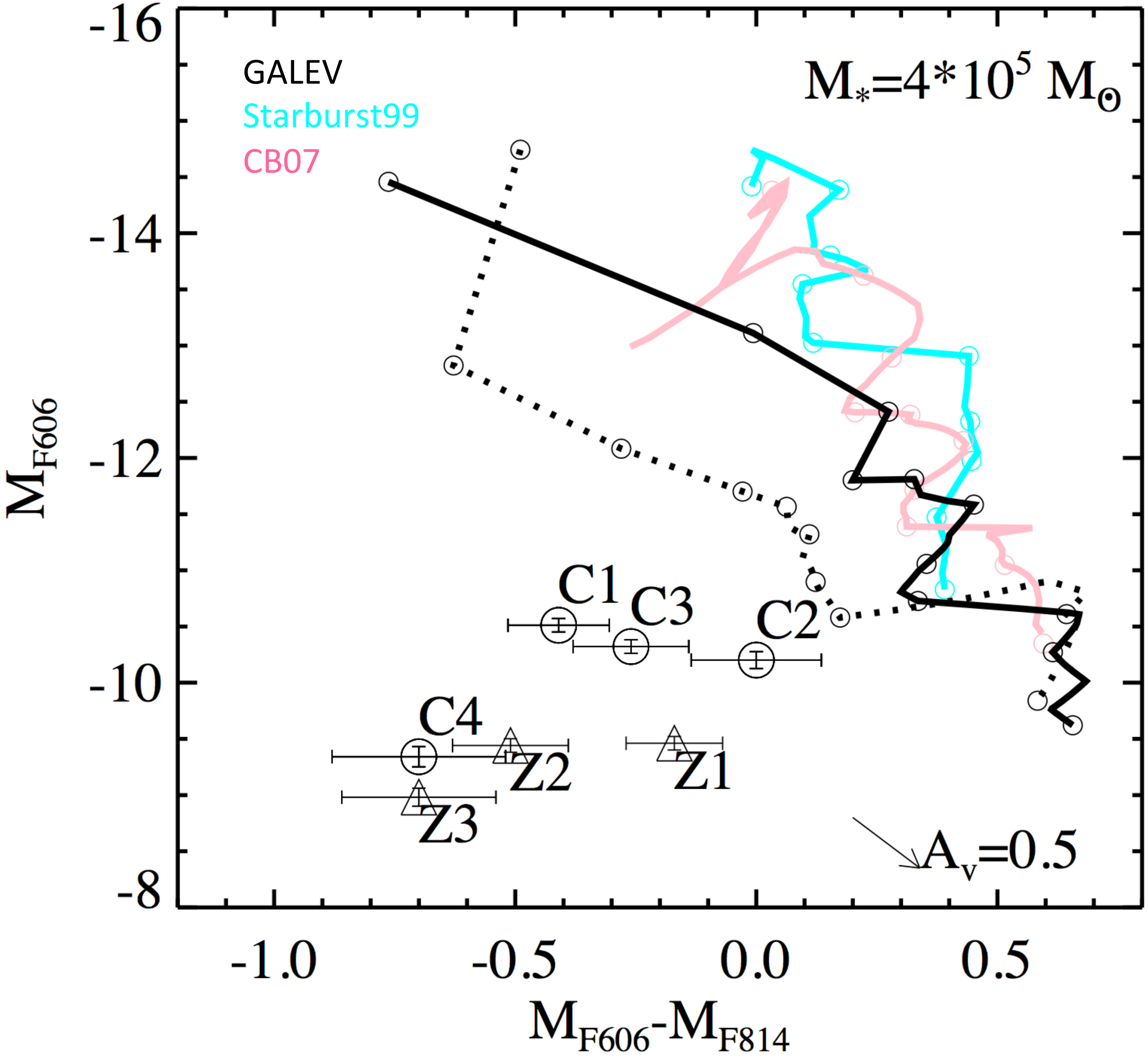
NGC602

58X58 pc

(Carlson et al. 2007)




C1
Z2
Z1
Z3
C2
C3
C4

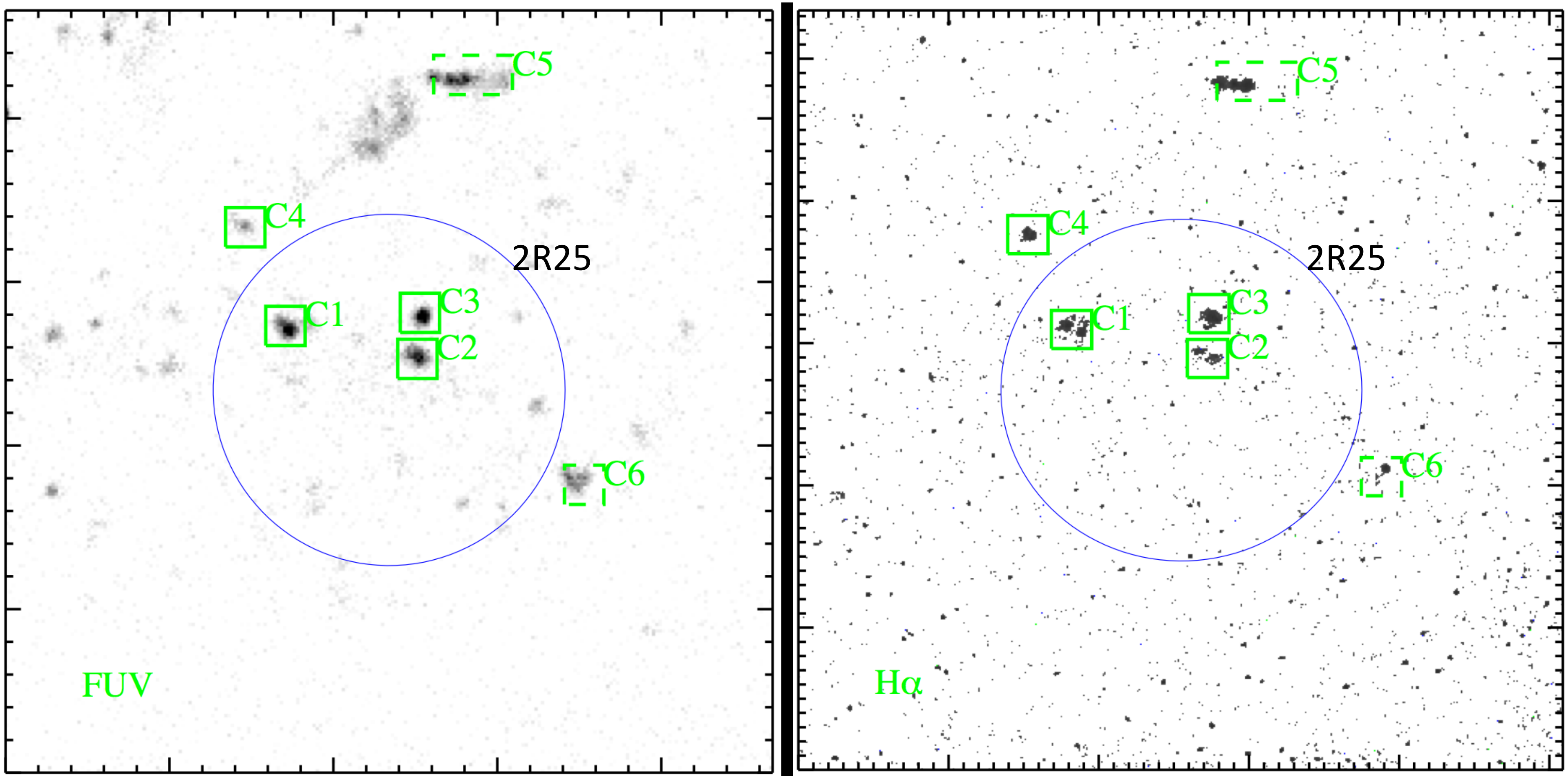


Age grids: 4,8,12,16,20,32,60, 100,200,500 Myr

GALEV (Kotulla et al.2009): Continuum +emission line

Starburst99(Leitherer et al. 1999): Continuum of stars and ionized gas

CB07 (Charlot & Bruzual 2007): Continuum of stars



4-6 star forming HII regions:

- 1-3 of them are outlying HII regions (dis >2R25). Werk et al.(2010): the overal frequency of outlying HII regions in gas-rich galaxies is 8%-11%
- The SFR contained in these regions are ~30% of the total SFR.

Attempt to understand the local SF in star forming regions with:

- The HI-SF efficiency: the K-S star formation law
- The Ostriker et al.2010 star formation model:

$$\Sigma_{SFR} = 3 \times 10^{-10} M_\odot pc^{-2} yr^{-1} (\frac{\Sigma_g}{10 M_\odot pc^{-2}}$$
$$\times [1 + 3(\frac{Z_d \Sigma_g}{10 M_\odot pc^{-2}})^{0.4}]$$
$$\times [\frac{2}{\alpha}(\frac{\Sigma_g}{10 M_\odot pc^{-2}}) + (\frac{50 f_w}{\alpha})^{1/2} (\frac{\rho_s + \rho_d}{0.1 M_\odot pc^{-3}})^{1/2}]$$

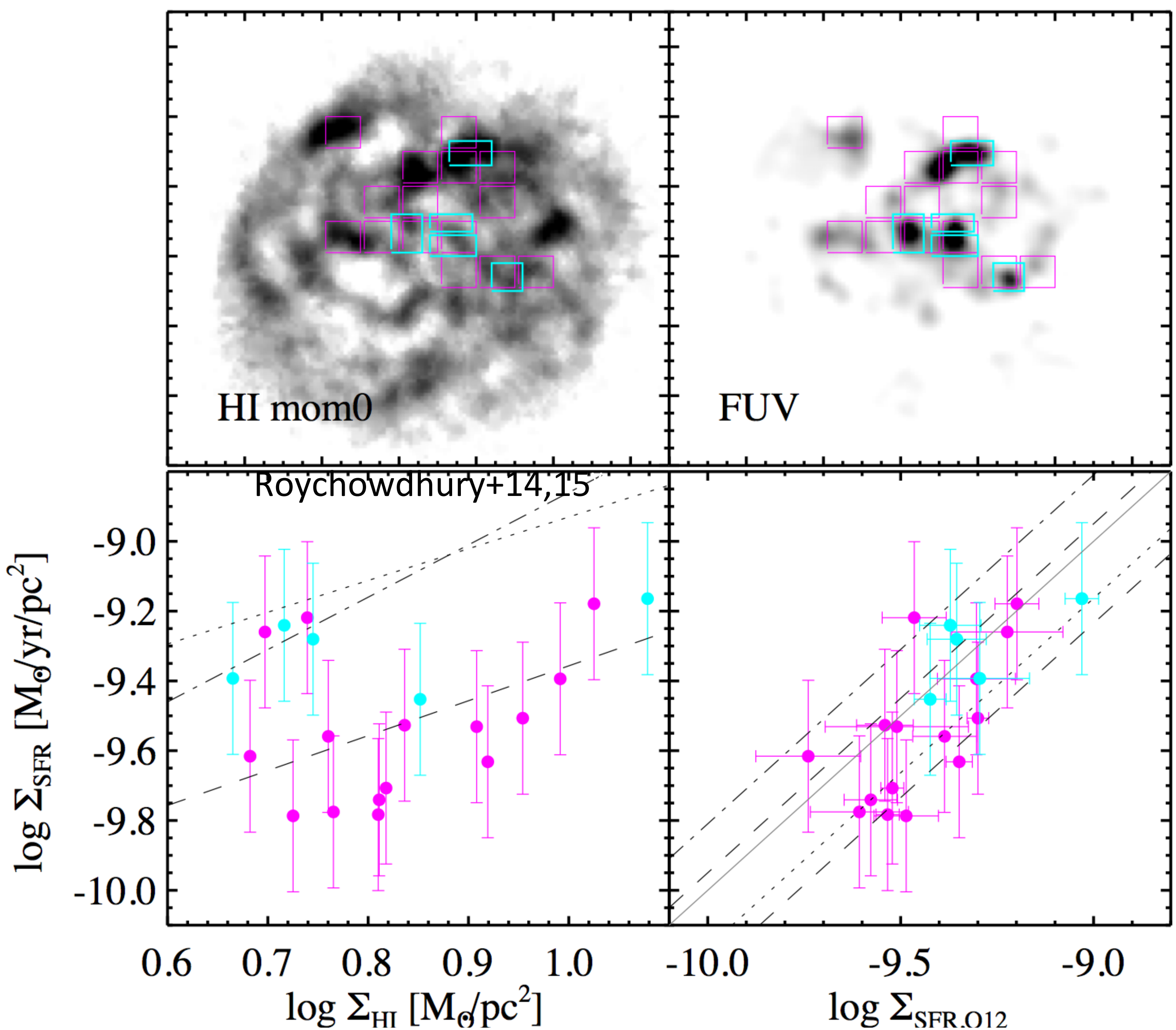
Σ_g Gas surfarce density

ρ_s Stellar volume density

ρ_d Dark matter volume density

Z_d Metallicity of dust (gas)

SFR in the star forming regions



1.2 kpc grids
SFR>0.0003
$M_{\odot}$/yr

The HII regions

Cause for the low HI-SF efficiency at a fixed Σ_{HI} in the star forming regions

How to understand the ~-0.5 dex offset from revised KS laws

The O10 model:

$$\Sigma_{SFR} = 3 \times 10^{-10} M_{\odot} pc^{-2} yr^{-1} (\frac{\Sigma_g}{10 M_{\odot} pc^{-2}} \times [1 + 3(\frac{Z_d \Sigma_g}{10 M_{\odot} pc^{-2}})^{0.4}] \times [\frac{2}{\alpha}(\frac{\Sigma_g}{10 M_{\odot} pc^{-2}}) + (\frac{50 f_w}{\alpha})^{1/2} (\frac{\rho_s + \rho_d}{0.1 M_{\odot} pc^{-3}})^{1/2}]$$

	parameter	ESO215-G?009	typical dwarf/spiral	$\Delta\Sigma_{SFR}$
	Z_d [$Z_{\odot}$]	0.23	1	0.16
	log Σ_{HI} [$M_{\odot}$ pc^{-2}]	0.81	0.81	0
Dwarf:	log Σ_{*} [$M_{\odot}$ pc^{-2}]	-1.1	1.1	0.39
Spiral:	log Σ_{*} [$M_{\odot}$ pc^{-2}]	-1.1	1.5	0.54

SF in ESO215-G?009:

The SF is efficient:

- The occurrence of outlying HII regions is frequent
- The SFR in star forming regions are consistent with its stellar mass surface density.

The SF is ineffcient:

- The SFR/HI in star forming regions are low because of low stellar mass surface density: low SF in the past. (lack of trigger in the past?)

  "no neighbors identified out to 1 Mpc" , Warren et al. (2004)
- The lack of star forming regions in the southern half of the HI disk. (SF happens in a stochastic way?)

Outline

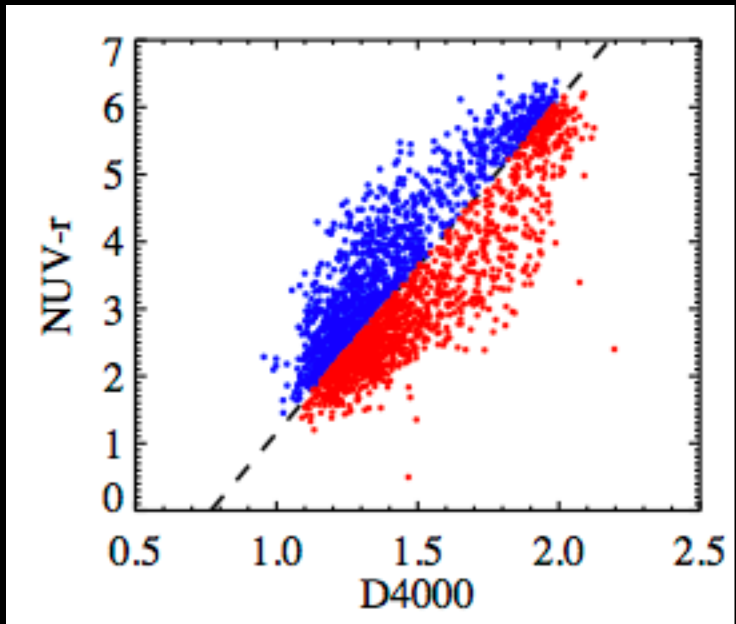
- How do galaxies obtain the cold gas?
- How is HI distributed in galaxies?
- How do galaxies form stars in HI-dominated regions?
- How is star formation quenched in galaxies?
- How do galaxies (trans-)form their structure with the cold gas?

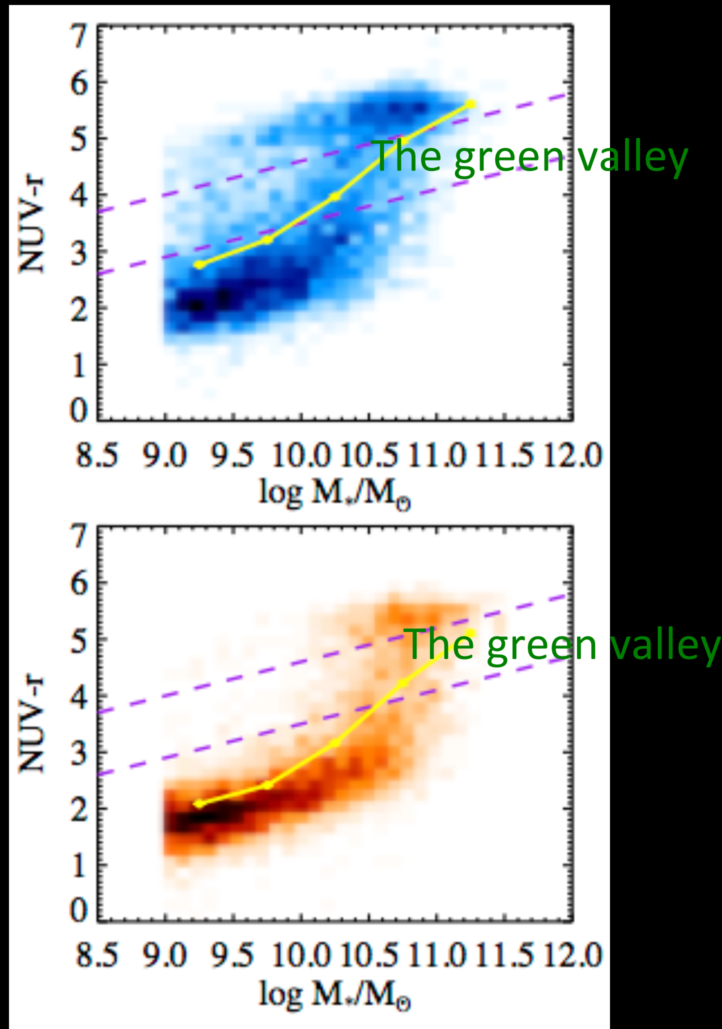
How is star formation quenched in low mass galaxies?

(Wang & Pan in prep)

QUENCHING OF STAR FORMATION IN GALAXIES

The star formation gradient of galaxies



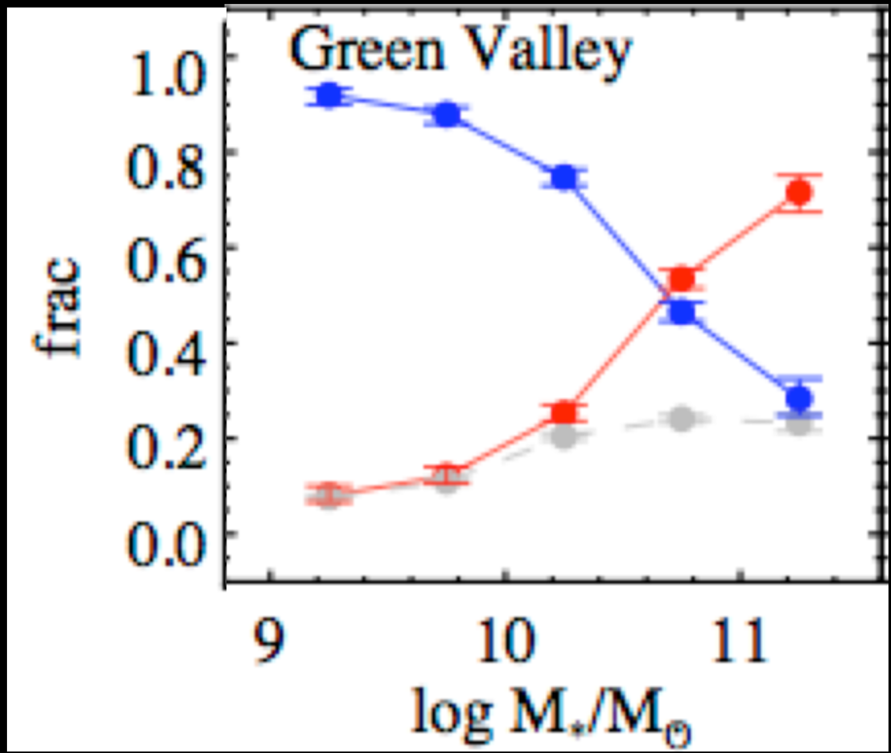


Blue-cored: outside-in

Red-cored: inside-out

(A modified analysis of Pan+14)

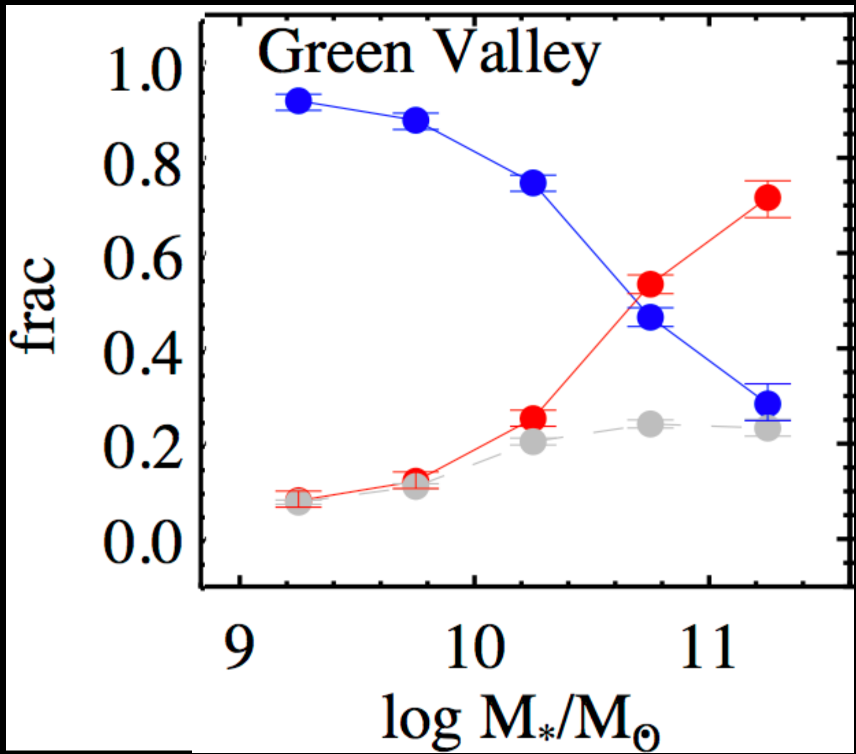
Galaxy assembly mode depending on stellar mass

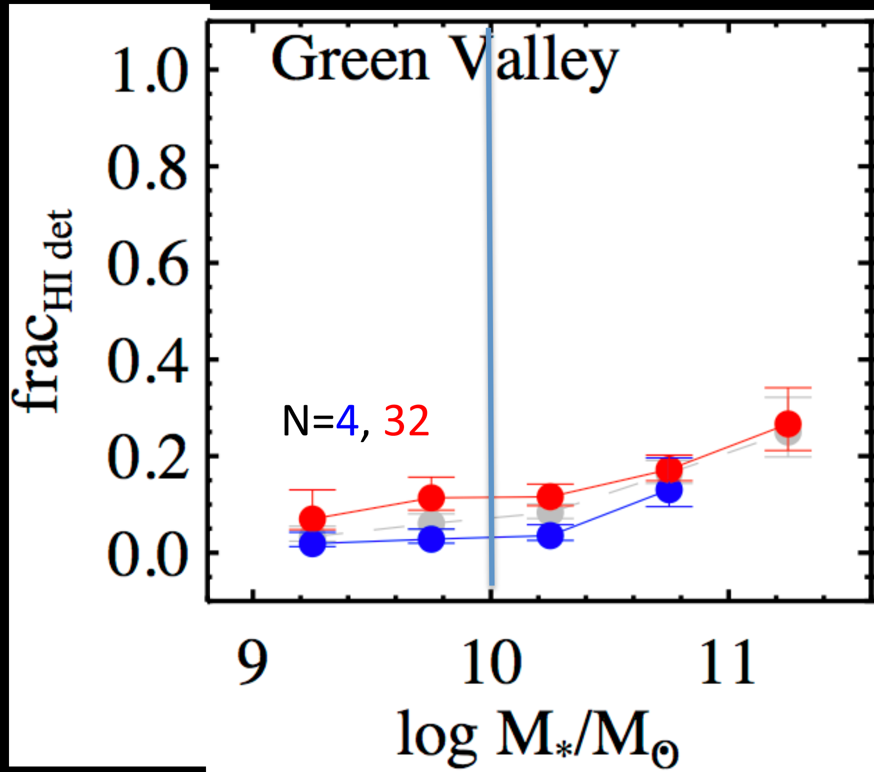


Blue-cored: outside-in (low mass galaxies)
Red-cored: inside-out (high mass galaxies)

(A modified analysis of Pan+14)

Cross-match with the ALFALFA.40 HI sample





Blue-cored: outside-in

Red-cored: inside-out

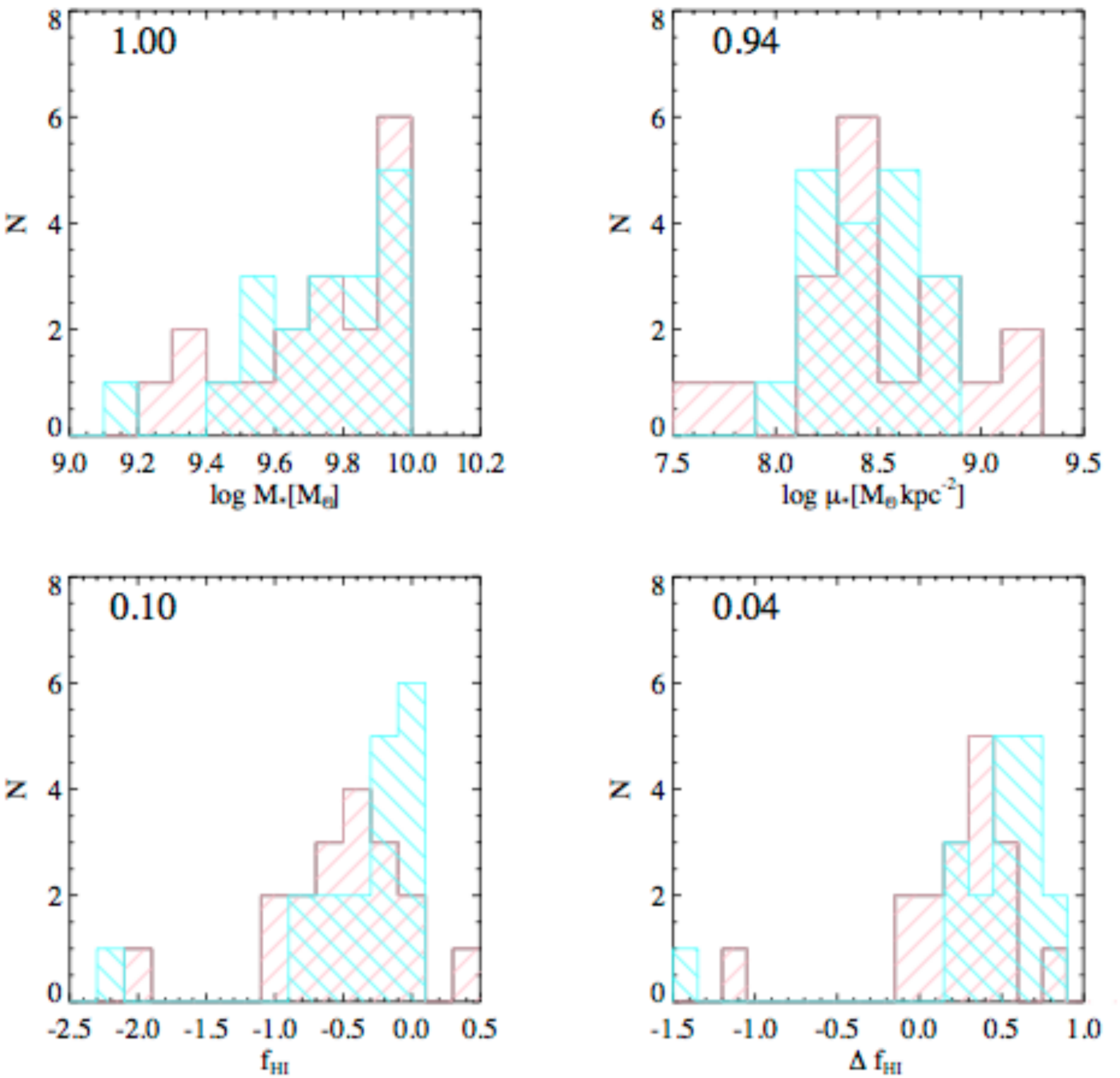
To increase statistics:

4+32= 18+18

18: less red-cored

18: more red-cored

The difference in HI mass



Less red-cored galaxies have more HI than More red-cored ones.

Quenching in low-mass GV galaxies (summary and caveats)

- The blue-cored ones are slight less likely to be detected in shallow HI surveys than the red-cored ones, however when detected the less red-cored galaxies are more HI-rich than the more red-cored ones: a non-continuity in HI content between inside-out and outside-in?

Statistic limits: with a one-year shallow survey, FAST is going to expand the size of the ALFALFA.40 sample used in this study by more than 70 times

- Limited by data available in other bands, dust attenuation and molecular gas not considered yet.

Outline

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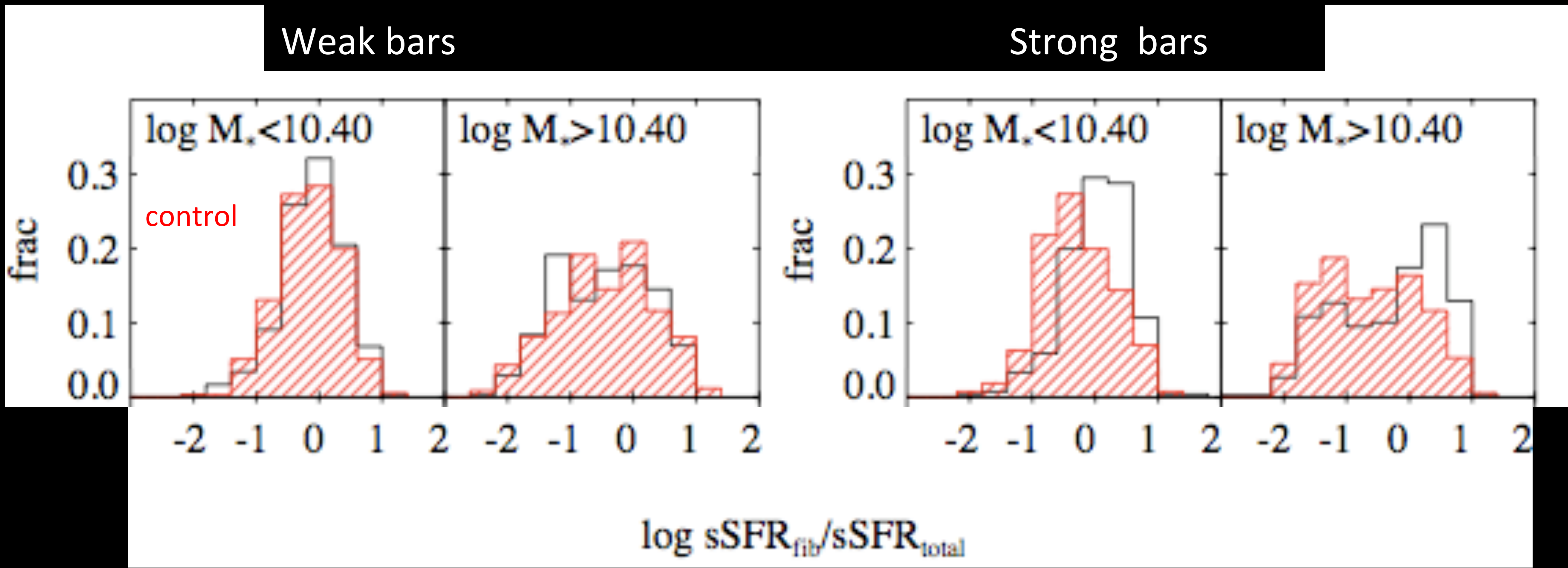
The the bulge, the bar and the outer disk (Wang+11, 12)

THE STRUCTURE OF GALAXIES

Bars in galaxies

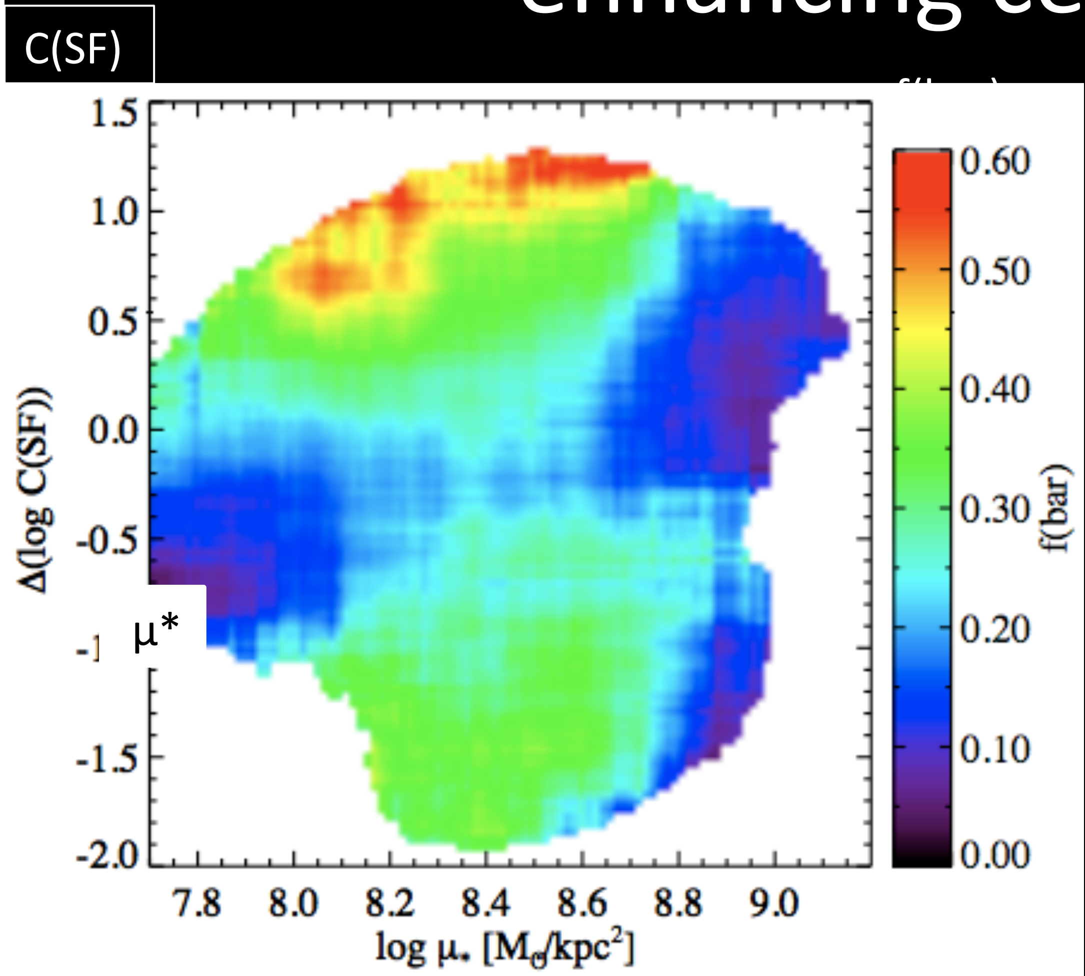
What kind of bars enhance central star formation



Strong bars: the bars with b/a<0.5
Only strong bars enhance central SF

Wang+11

How important are strong bars in enhancing central SF？



The galaxies which have highest C(SF) also have highest bar fraction ～60%

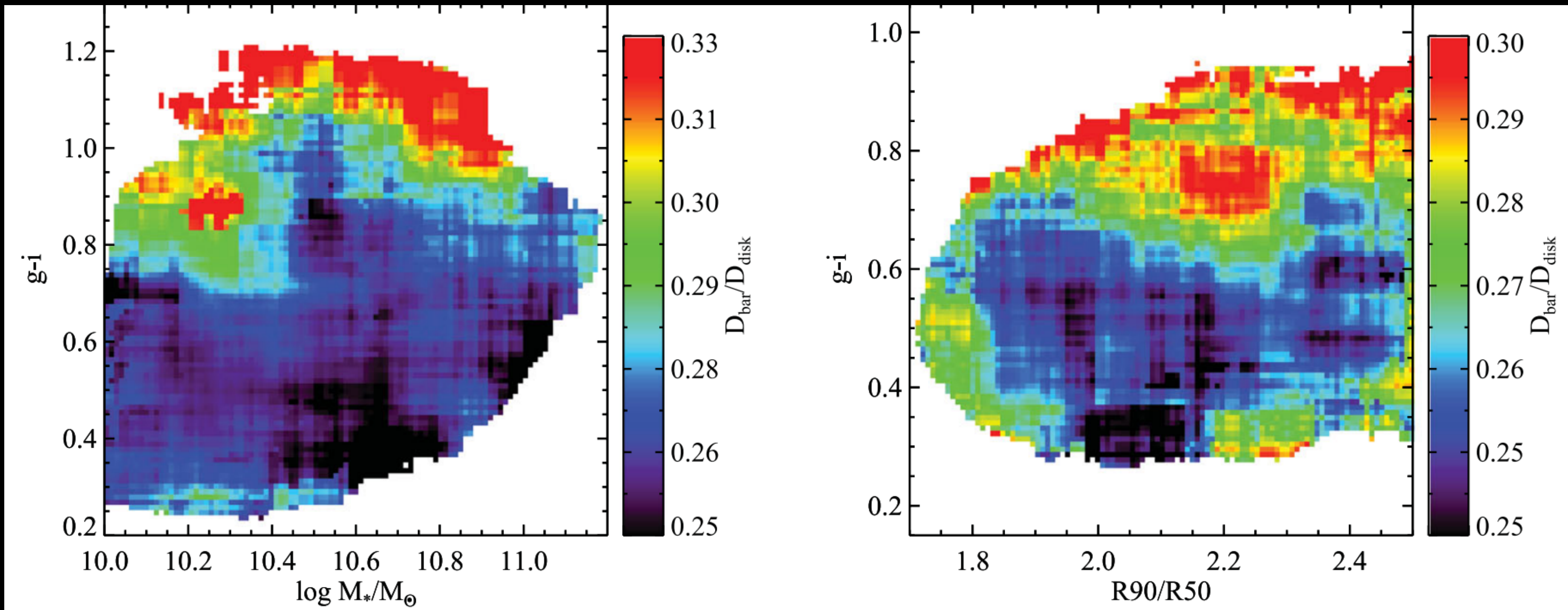
- Bar is one of the most important mechanisms in inducing central SB

Bar fraction show double peaks along C(SF)

- Bar may be related to the central SF quenching.

Wang+11

Bar length depending on color



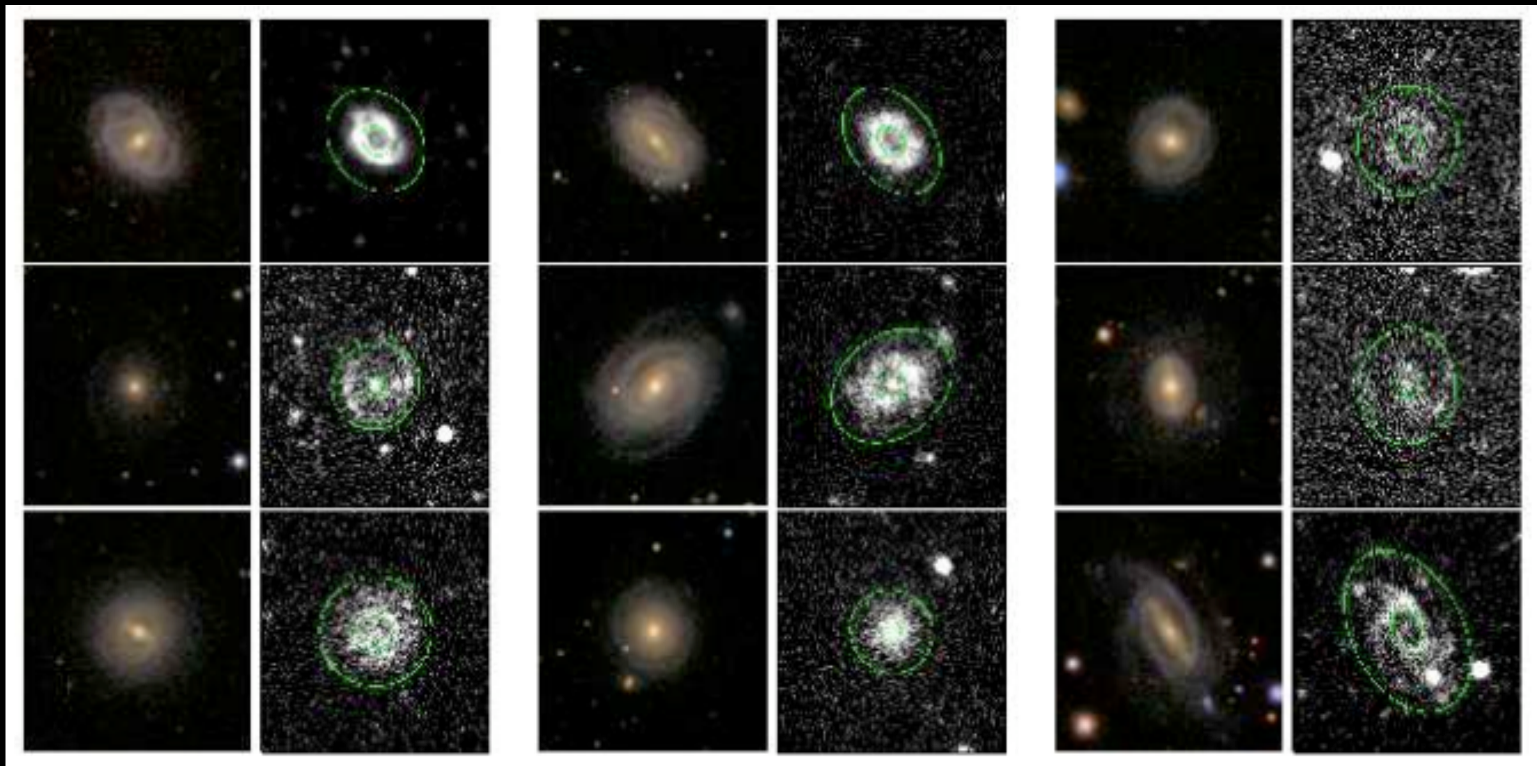
Cold gas may suppress bars.

Wang +12

Morphology of the inside-out galaxies

The galaxies with the most negative colour gradients:

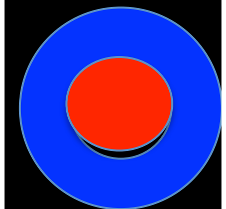
optical UV

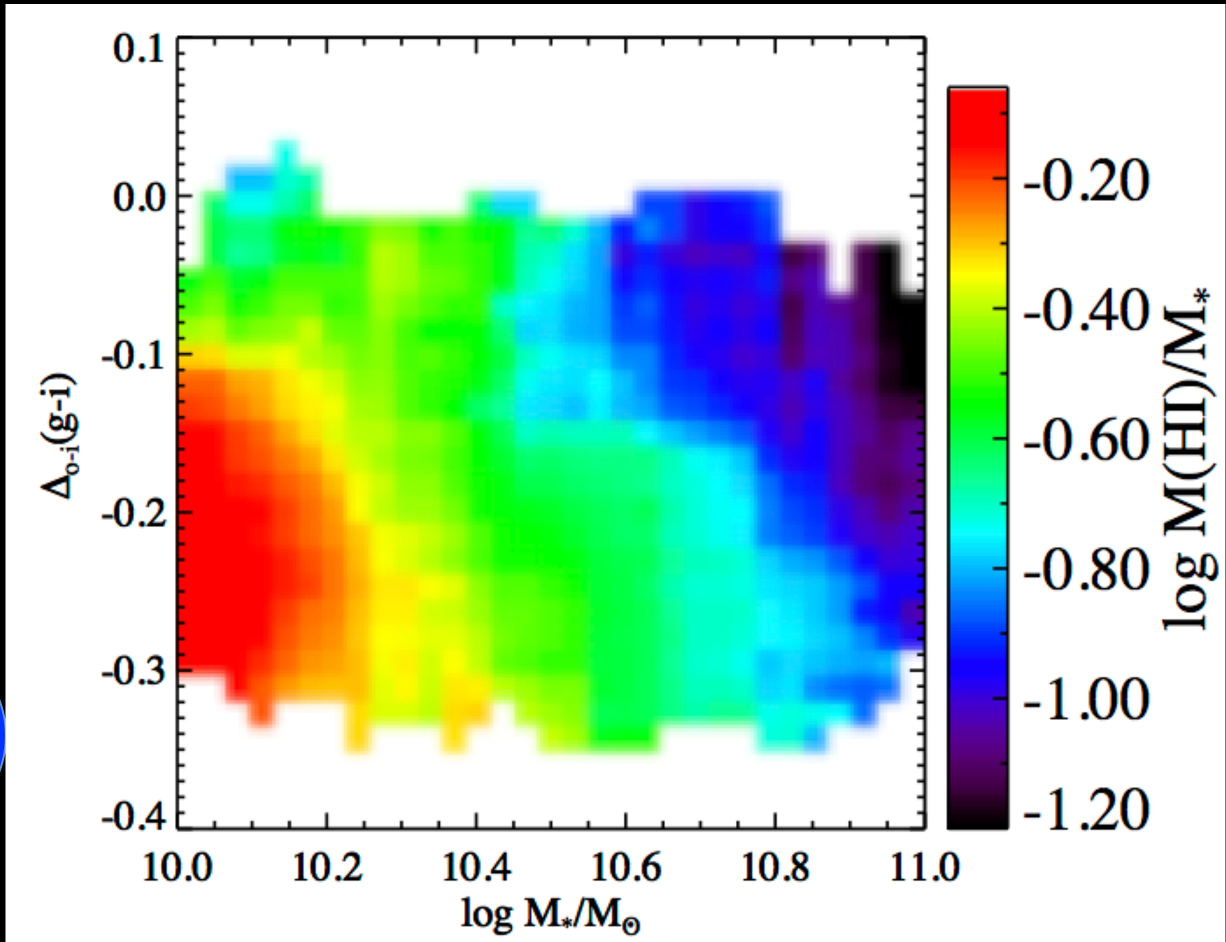


Wang+11

UV bright “ring”（which is not so clear in the optical)

The relation between M_{HI}/M_* and color gradients

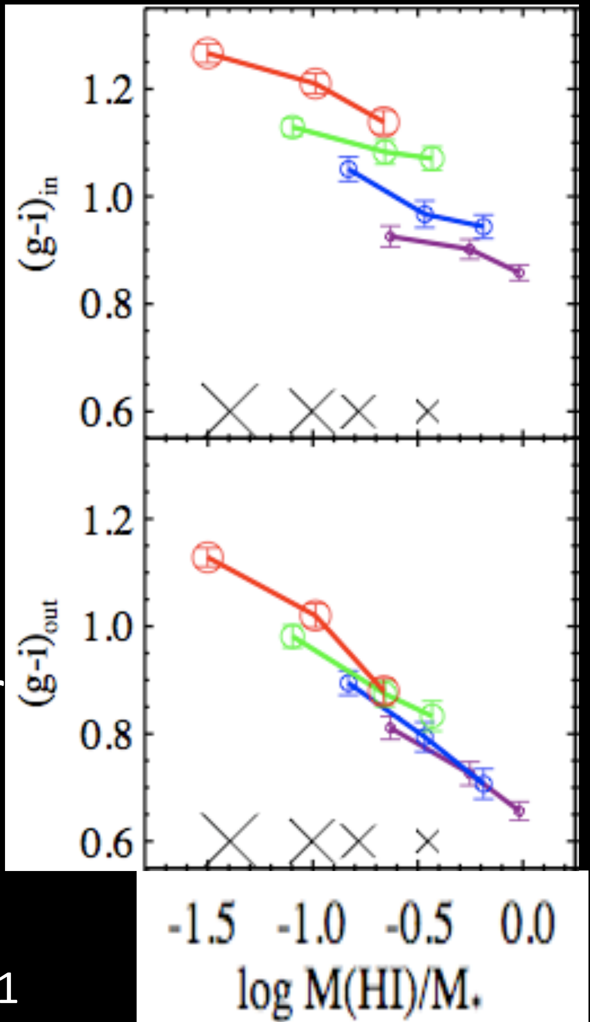




Wang+11

Relation between HI Gas and Growth of Inner and Outer Regions

inner



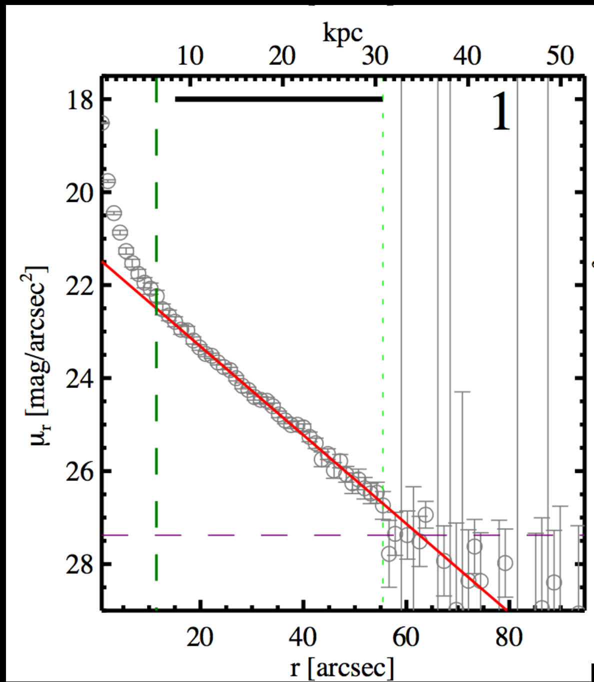
outer

Mostly determined by M* → Inner regions reflect down-sizing

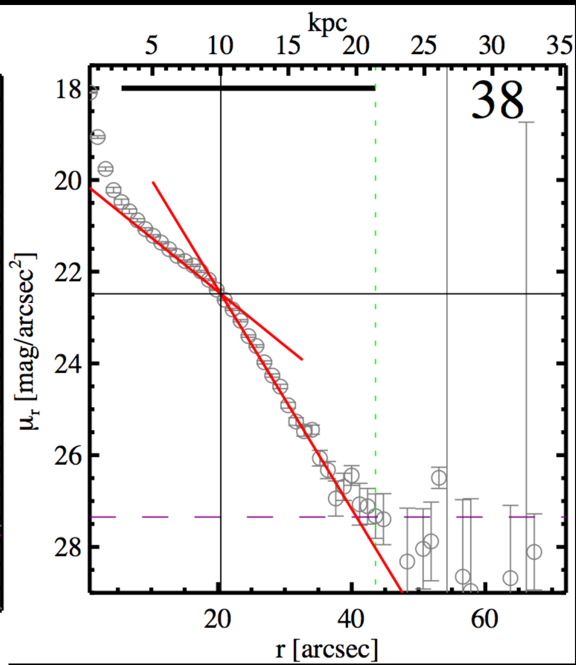
Mostly determined by HI fraction → Outer regions reflect influence of gas accretion

Wang+11

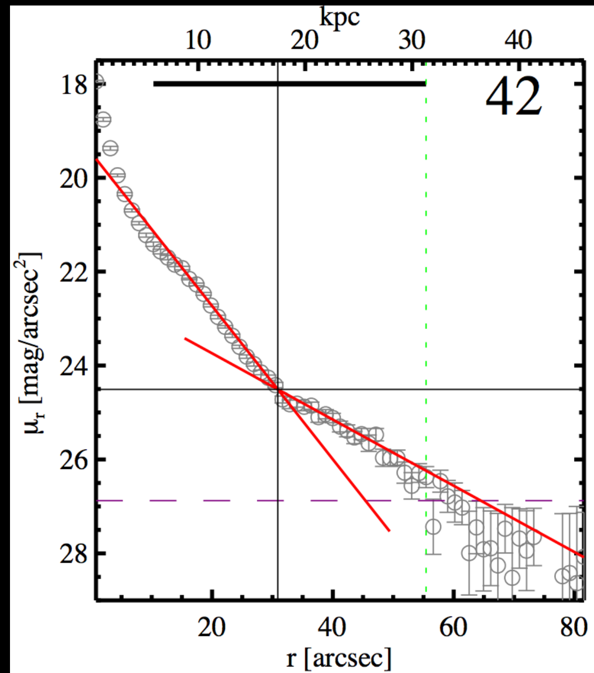
The outer disk structure in the optical



Pure exponential



down-bending



up-bending

wang+ in prep

HI may build up-bending disks

Sample		HI rich			HI poor		
	total	exponential	down-bending	up-bending	exponential	down-bending	up-bending
Bluedisk	27	5	1	6	0	13	2
GASS	48	7	2	7	11	14	7
ALFALFA	192	7.7%	43.1%	49.1%	9.2%	73.7%	17.1%

wang+ in prep

The cold gas has an important influence on

- the built of central mass concentration due to the inflow driven by bars
- the amplitude of bars

(In these bar related studies, we used star formation to indicate the status of gas (atomic and molecular). Optically defined HI surveys needed. FAST?)

- the inside-out growing stellar disks

(The only study in this section based on a stellar mass limited HI sample.)

- the bending of outer disks

(A large and optically defined HI sample needed. FAST?)

Summary

- Galaxies at low redshift accrete their gas in a gentle way, possibly from a reservoir present in the Mpc-scale environment.
- HI is distributed in galaxies in a remarkably uniform way, which raises challenges for existing models of galaxy formation.
- Star formation rate in HI dominated regions is possibly regulated by stellar mass surface density.
- The evolution of GV low M* galaxies are complicated as revealed by the HI content with current data.
- The excess HI gas mass in massive galaxies is connected with the inside-out growing optical disks, and the up-bending outer structures of the optical disks. The distribution of gas and the optical bar structure affect each other, and affect the built of central stellar mass concentration.

A lot of the limitations in the studies can be overcome with the new radio facilities including the FAST telescope.

HI science is in front of a golden age.